ALLOCATION OF CONGESTION MANAGEMENT AND VOLTAGE REGULATION COST USING POWER TRACING APPROACH

by

AJAY KUMAR

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

February, 2001

ALLOCATION OF CONGESTION MANAGEMENT AND VOLTAGE REGULATION COST USING POWER TRACING APPROACH

A Thesis Submitted
In Partial Fulfilment of the Requirement
for the Degree of

MASTER OF TECHNOLOGY

By

AJAY KUMAR

to

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

FEBRUARY, 2001

Certificate

It is certified that the work contained in the thesis entitled **ALLOCATION OF CONGESTION MANAGEMENT AND VOLTAGE REGULATION COST USING POWER TRACING APPROACH** by *Ajay Kumar* has been carried out under our supervision and that this work has not been submitted elsewhere for a degree

(Dr. B. C. Pal)
Assistant Professor
Department of Electrical Engineering
Indian Institute of Technology
Kanpur-208016

(Dr. S. C. Srivastava)
Professor
Department of Electrical Engineering
Indian Institute of Technology
Kanpur-208016

February, 2001

Acknowledgement

On the completion of the work, I feel it as my great privilege to work under the noble and esteemed guidance of Dr. S. C Srivastava and Dr B C Pal I can not forget them for excellent supervision, skilled guidance, unfailing support and constant encouragement not only during my thesis work but also during my whole stay at I I T Kanpur I find no suitable words to express my gratitude toward Dr S C Srivastava and Dr. B. C. Pal for his deep concern he has shown for my academics

I am very much thankful to professors S Sachchidanand, S S Prabhu and G. K Dubey who taught us various courses needed for this work

I am grateful to MHRD for sponsoring the project MHRD-20000024, "Integrated operation of power system in deregulated environment" Under this project Power World Simulator has been procured which was utilized in this work

I am thankful to Mr Anurag, Mr. Jagdish, Mr Ankush, Mr B J Naidu, Mr Hari and Mr. Krishna Rao for their invaluable suggestions.

Last but not the least, I would like to thank almighty God and my family members who made me to reach this stage, where I could undertake the work of this magnitude.

Ajay Kumar

Abstract

The electric utility industry, worldwide, is undergoing restructuring and deregulation The main objective of these changes is to allow for competition among various market players, to offer a low price, higher quality and more secured product. These changes call for many new practices to the power system operation and are also accompanied by variety of problems. Under a competitive environment, generation is not centrally dispatched, but rather, it is based primarily on the transactions agreed to in the open market In the market situation, the difficulty lies in ensuring the negotiated transactions, particularly under congestion and also maintaining system bus voltages within limit. The task is generally carried out by an independent system operator (ISO), through purchase of additional real and reactive powers from ancillary sources in the system An optimal power flow based method has been used in this work to compute the additional generation required from ancillary sources to remove congestion without curtailment of bilateral transactions Real power tracing has been utilized for equitable allocation of cost of the congestion management among various market participants. Voltage profile management has been achieved through additional reactive power purchased from ancillary sources in the form of shunt compensatory devices. Allocation of cost of the voltage regulation has also been suggested by using reactive power tracing. Studies have been conducted on modified IEEE-14 bus and IEEE-30 bus systems. The proposed method shows quite fairness in allocation of cost of congestion and voltage regulation to the market participants

Contents

List of figures

List of Tables

Chapter 1

Introduction

1.1 General

Commercial operation of electric power systems dates back to late 19^{th} century During all these years the electric industry has under-gone many changes but electric power industry nearly in every country has operated as a regulated monopoly. i.e as a single utility having control over generation, transmission and distribution.

Since the last decade, the electric industry is going through restructuring due to many factors in the globalize business environment The aim of this development is to open up market and to give consumers the opportunity to purchase energy at more favorable prices. Different countries adopt different types of market liberalization models. In some countries, the liberalization of the power market has already taken place, in others it is under implementation or discussion stage.

The forces behind electric sector deregulation, taking place worldwide, have either been political reform, regulatory failures, high tariffs, managerial inefficiency or global economic crises. Many countries have made the changes as a result of the failure of the state to adequately manage electricity companies and also the lack of public resources to finance the required investment for development. The conditional loans from international funding agencies such as World Bank, Asian Development Bank are clear indication of encouraging unbundling of electricity supply system

As a result of deregulation, the market system will consist of several generation companies (GENCOs), transmission companies (TRANSCOs), distribution

companies (DISCOs), energy service companies (ESCOs), ancillary services companies (ANCILCOs), independent system operator (ISO), regional transmission group (RTGs) and national electricity regulatory commission (NERC) 'Deregulation' word is being used in a loose sense for restructuring the electricity sector in order to bring competition amongst various market players It does not mean absence of 'regulation'. A correct terminology for this purpose can be 'Re-regulation'. This essentially means the separation of various tasks, those are being carried out in the traditional system, to enable competition and to arrive at the cheaper production price

This changing environment decisively influences further development and optimization of transmission networks The power flow pattern can change considerably. The ancillary functions are required for smooth operation of the networks, such as load frequency control, voltage control The important tasks of system security are now in the hands of the system operator.

In a deregulated market, there may be large number of different buyers and sellers combinations. The transmission and distribution losses are inherent in electricity trading. Additional production is needed to meet these losses The two basic characteristics of electric power network have to be properly handled viz transmission congestion and voltage regulation. These are handled by a third party who is neither buyer nor seller of the electric energy i.e Independent System Operator (ISO) ISO also maintains power flow balance throughout the network and includes the transmission losses in the power balance

In a regulated monopolistic power market, the scheduling of generation is done following a centralized unit commitment and economic dispatch algorithm such that all transmission limits are satisfied. Under a competitive environment, the generation is not centrally dispatched. It is based primarily on the transactions bidding and market settlements. To fulfil the generation bids, transmission congestion may occur due to heavy loading of transmission lines. In a market situation, the difficulty lies in ascertaining negotiated transactions and to operate the transmission system in a secure state. In some situations, transmission congestion can be relieved by technical means,

such as with the use of flexible AC transmission system (FACTS) controllers and by providing ancillary generators at different locations

1.2 State of the Art

The general motive for restructuring is to enhance the efficiency of the electric power industries How the restructuring is being or to be carried out is a political issue and the solution differ from one country to the other So far, there is no single solution to how the restructuring should be accomplished The significant contribution in the literature on this field is found in the books by Philipson et al. [3] and Illic et al [4] In these books, most fundamental issues of restructuring are discussed

Deregulation of power industries give rise to a debate on the following power system operation aspects

- How the transmission system should be restructured?
- How the transmission pricing should be made in the open access?
- How the contracts shall be made between generating companies and customers?
- How the transmission congestion should be managed by ISO?
- How the transmission losses shall be allocated to the market participants?
- How the congestion relief cost shall be allocated to the market participants?
- How well the compensatory devices will play an important role in the competitive environment etc?

Brat et al. [20] had presented a method for the power and energy management according to minimal costs criteria over one year of an electricity utility, having nuclear and hydro power plants considering fixed contracts, variable contracts and exchange contracts Berrizzi et al. [12] had suggested a model based on security constrained optimal power dispatch considering firm contracts and interruptible contracts that maximizes the real power exchange amongst the different agents of the electricity market Conejo et al. [24] presented a framework to carry out a multi-area optimal power dispatch in a coordinated decentralized fashion. David et al [26,11,24]

modeled power transactions in deregulated market under open transmission access as pool dispatch and bilateral dispatch A transaction namely ancillary services transaction has been introduced for providing essential ancillary services including transaction for transmission loss compensation A typical five bus system was considered for illustrating the transaction curtailment strategy under transmission congestion. The objective of the ISO is considered as to maximize the generation cost minus delivery prices A component called as 'willingness to pay' in case of congestion to avoid curtailment was also included Zobian and Marrija Illic [29] has introduced the concept of each transaction to the network power flows through out the interconnected power system in the steady state operation. The concept of distributed slack bus was introduced to account for the fact that many generators are participating in economic power dispatch. Formulation was done with the assumption that shunt impedance of the lines can be neglected Yu and David [31] gave the security related long run marginal cost Analysis of transmission services, the security related marginal wheeling costs of transporting power between buses were carried out using the sensitivities of the MW-mile of each area with respect to bus power demand Daniel Kirschen et al [15,26] proposed a new method of real and reactive power tracing The method provides information such as which generators are supplying a particular load, how much use each generator is making of a transmission line and what is each generators contribution to the system losses The applicability of the proposed technique is demonstrated using a 30-bus example Fang and David [9], proposed a new scheme of rescheduling transactions under congestion of the transmission system The new set of transaction was the closest point near the desired transactions within the security region. A minimum distance algorithm was presented by Galiana et al [17,23,4] as a means to allocate limited transmission capacity under congested conditions to set up transactions proposed by the market forces. This algorithm was used to reschedule proposed transaction as well as to trade reserved transaction rights to allocate transmission losses. Transmission congestion cost had been dealt by Harry singh et al. [18]. They proposed two approaches for dealing with these costs The first approach is based on nodal pricing framework and forms the basis of the pool-model

The second approach is based on cost allocation procedures for the bilateral contracts Mesut et al [7] investigated a bid based congestion management scheme for a system that accommodates many bilateral transactions. The method reflects the actual usage of the congested facilities by the transactions and recovers the cost They also proposed "consistency" test to quantify and test the equity of the method. The results on consistency indicates that the proposed method is consistent provided that the transactions causing counter flows on congested lines are compensated

The new electrical sector regulation stresses the role of competitive markets for the procurement and remuneration of ancillary services Among these services stand the ones associated with reactive power supply and voltage control services. Julian et al [8] decomposes reactive power supply and voltage control services in two types.

(i) Voltage profile management and reactive dispatch

(ii) Voltage regulation

A theoretical approach based on marginal pricing is proposed to remunerate the suppliers and to charge the consumers of these services.

1.3 Objective of the Thesis

Many developing countries are adopting deregulation in their electricity market. When the deregulation of the power system is introduced, the usage of the existing available generation capacity to its maximum extent, fulfillment of transactions in open market and operation of the power system in the secure state become the prime objectives It is also important to relieve the congestion and to allocate the cost of congestion management to the market participants and to operate the system in secure state. Hence, the objectives of the present work have been

- To evolve a systematic and simple approach of managing the congestion without curtailment of the transactions. The suggested method uses the ancillary generators in the system for relieving the congestion and makes use of an optimal power flow (OPF) package.

- To evolve a simple approach for allocating the cost of congestion management to the market participants. The suggested method traces the contribution of the sources to active line flows and cost of congestion is allocated to the market participants, in proportion of their usage of the line
- To consider the voltage profile management The suggested method traces the contribution of sources to reactive line flows and loads at buses and cost of voltage regulation is allocated to market participants in the proportion of their supplying loads at buses.

1.4 Thesis Organization

The thesis has been organized in four chapters as described below

Chapter 1 introduces various aspects and problems associated with deregulation of electric power industry and the role of optimal power dispatch in management of transactions. It presents a brief state of the art and sets the motivation behind the work reported in the thesis

Chapter 2 presents a concept and algorithm of tracing real and reactive line flows to find the contribution of sources to the line flows and loads

Chapter 3 present a method of allocating cost of congestion and voltage profile management by using real and reactive power tracing An OPF routine available in Power world simulator package has been used to handle congestion without curtailment of transactions.

Chapter 4 concludes the main findings of the thesis and lists a few suggestions for future scope of work.

Chapter2

Tracing Active and Reactive Power Flows

2.1 Introduction

In many parts of the world, the electricity supply industry is undergoing restructuring. While these changes are taking many forms such as separation of traditional vertically integrated utilities into generation, transmission and distribution companies, introduction of retail wheeling, creation of markets for electric energy, the main goal is the introduction of competition towards the lowering of the average consumer price.

While competition is introduced in generation and retail (or supply), it is widely agreed that transmission will remain a natural monopoly and centrally controlled It is also widely recognized that the operation of the transmission system can have an enormous impact on a competitive market. Competition will flourish only if all actual and potential market participants are convinced that the market is operating fairly.

Transparency in the operation of the transmission system is an essential fact in establishing this confidence. In this respect, generators, suppliers and network operating companies would like to get accurate and indisputable answers to questions such as "How far is the power generated by an unit really going?" or "Which generators are supplying a given consumer?" or even "Which generator is making the biggest use of a transmission line?". Before the introduction of competition, these questions were of limited and mostly academic interest because all of the power was generated by the same utility company or bought under fairly straightforward contracts. Furthermore, conventional wisdom suggested that, except for radial networks and other special configurations, they did not have any answer.

Since the introduction of competition in various countries around the world and the introduction of wheeling, these questions have to be addressed in various forms. In [26], a new scheme has been suggested for determining which generators are supplying a particular load, how much use each generator is making of transmission line and what is each generator's contribution to the system losses The proposed technique is not limited to incremental changes and is applicable to both active and reactive power Starting from a power flow solution, the technique first identifies the buses, which are reached by power produced by each generator. Then it determines the set of busses supplied by the same generators. Using a proportionality assumption, it is then possible to calculate the contribution of each generator to the loads and flows

Ref. [15] proposes a method for determining how much of active and reactive power output of each generator is contributed by load Applying the principles of contribution method require the simultaneous consideration of both active and reactive effects. However, combinations of independently computed active and reactive power contributions is not possible because of the interaction introduced by the losses and the fact that the line flows usually have different power factors. To get around this difficulty, this method takes a solved power flow solution, as its starting point. All power injections are translated into real and imaginary currents to avoid the problems arising from the non-linear coupling between active and reactive power flows caused by losses. The method then traces these currents to determine how much current each source supplies to the sink. These current contributions have then been translated into contributions to the active and reactive power output of the generators. It was found reasonably accurate for the reactive power generation. To determine the contributions to active power generation, the method reported in [26] was recommended based on the active power flows without providing any comparison of result from the two methods

In this chapter, both real and reactive power tracing algorithms have been developed. The reactive power tracing algorithm is based on the approach suggested in ref. [15], However, two algorithms of real power tracing have been developed based on real power tracing [26] and complex current flow tracing [15]. The applicability of the method has been conducted on modified IEEE-14 bus and IEEE-30 bus systems.

2.2 Concepts and Algorithms

Based on the active flows from a solved power flow, the method [15] organizes the buses and branches of the network into homogeneous groups according to a few concepts, which are introduced below It is also possible to represent the state of the system by a directed, acyclic graph. Further processing of this graph gives the contribution of generator to line flows This method is applicable individually to both active and reactive power flows

Domain of a Generator: The domain of a generator is defined as the set of buses which are reached by power produced by this generator. Power from a generator reaches a particular bus if it is possible to find a path through the network from the generator to the bus for which the direction of the flow is computed by a power flow program

To illustrate the concept, consider a 6-bus example as shown in Fig 2.1. It can easily be seen that, for the system shown in Figure 2 1, the domain of generator A encompasses all the busses while the domain of generator B includes only bus #3, #4, #5 and #6 and the domain of generator C is limited to bus #6. As could be expected, there is a significant overlap between the domains of the various generators

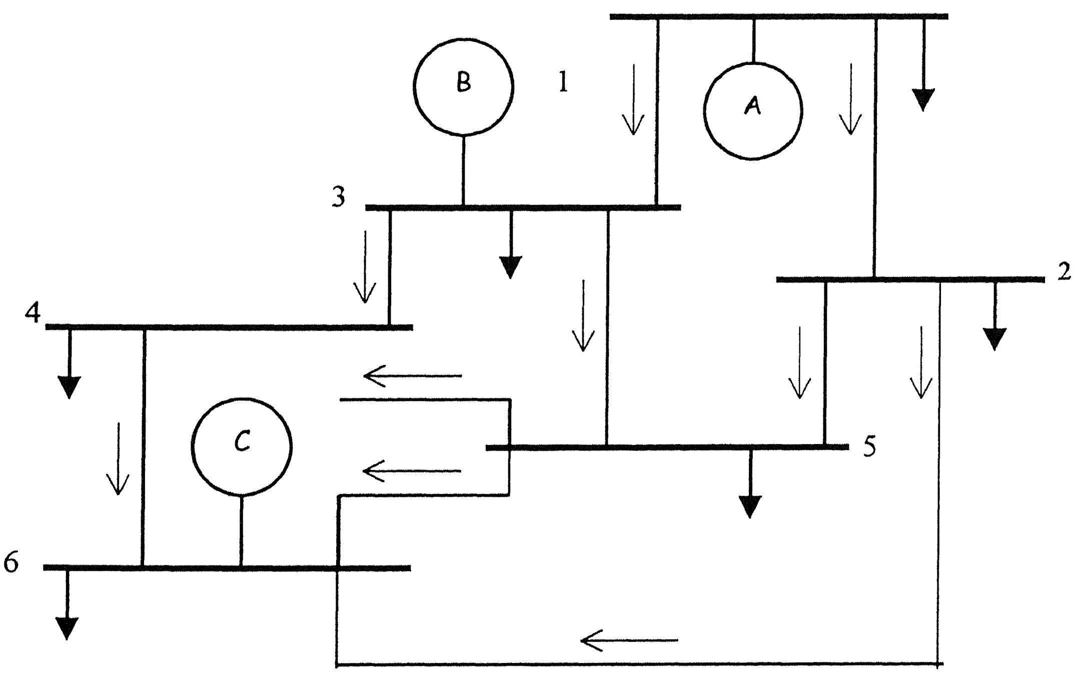

Figure2.1· A-Six bus example

For larger system, the domain of a generator can be determined using the following steps

Step 1: An incidence matrix is formed by using branch flows from a solved power flow Incidence matrix is a square matrix of the order equal to the number of buses in the system The elements of the incidence matrix are +1, -1 or zero If the branch flow is away from bus say 'a' and towards bus say 'b', then element in incidence matrix corresponding to row 'a' and column corresponding to 'b' is +1, else row corresponding 'b' and column corresponding to 'a' is –1 If buses 'a' and 'b' are not connected then corresponding element will be zero.

Step 2· Using the above incidence matrix, domain of a generator can be found by looping over all the branches connected to generator bus A recursive method has been used to found domain. Say, if a generator is connected to bus 'a', then all +1 elements of the row (say j^{th} column) corresponding to 'a' in the incidence matrix are included in the domain of the generator Then again go to the j^{th} rows and search for buses corresponding to +1 elements. The buses corresponding to +1 are added to the domain of generator if it is not added to domain of generator earlier

Note. The "active domain" of a generator does not usually cover the same set of buses as its "reactive domain".

The concept dual to the domain of a generator can be defined as the catchment area of a load. Which is the set of buses, reached by power, consumed by this load. Its extent can be computed using the same algorithm as above but starting from the load and considering only the branches which carry power flowing towards the load. In the example of Fig. 2.1, the catchment area of a load connected to bus#5 includes bus #5, #3, #2 and #1 and hence generators A and B.

Commons: The domain of a generator is a good concept but its applicability is limited due to heavy overlap between the domains of the various generators The concept of commons is more useful, albeit somewhat less intuitive. A common is defined as a set of contiguous buses supplied by the same generators. Unconnected sets of buses supplied by the same generators are treated as separate commons. A bus therefore belongs to one and only one common. The rank of a common is defined as the number of generators

supplying power to the buses comprising of this common. It can never be lower than one or higher than the number of generators in the system

The example of Fig. 2 1 contains three commons

- Bus #1 and #2 which are supplied by generator #1 only (common 1, rank1)
- Busses #3, #4 and #5 which are supplied by both generators #1 and #2 (common2 and rank2)
- Bus #6 which is supplied by all three generators (common 3, rank 3)

For networks of a more realistic size, the following steps determine the common efficiently

Step 1. Using domain of generator, record with each bus the generators, which supply this bus

Step 2 Loop over all the buses. If a bus is not yet part of common, create a new common based on the generators supplying this bus.

Step 3 Recursively propagate this common to all buses connected to this bus

Links: Having divided the buses into commons, each branch is either internal to a common (i e it connects two buses which are part of the same common) or external (i e it connects two buses which are part of different commons) One or more external branches connecting the same commons from what will be called link It is very important to note that the actual flows in all the branches of a link are in the same direction. Furthermore, the flow in a link is always from a common of rank N to a common of rank M, where M is always strictly greater than N

In the example of Fig 2.1, there are three links:

- Link 1, which connects commons 1 and 2 and consists of branches 1-3 and 2-5.
- Link 2, which connects 2 and 3 and consists of branches 4-6 and 5-6.
- Link 3, which connects commons 1 and 3 and consists of branch 2-6

Branches 3-4, 3-5 and 4-5 are internal to common 2 Branch 1-2 is internal to common 1. There are no internal branches in common 3

State graph: Given the direction of the flows in all the branches of the network, the algorithm described above produce unique sets of commons and links. If the commons are represented as nodes and the links as branches, the state graph of the system can be represented by a directed, acyclic graph. This graph is directed because the direction of

the flows in a link is specified. It is acyclic because links can only go from a common supplied by fewer generators to a common supplied by more generators Typically, the root nodes of such a graph corresponds to a common of rank one while the leaves consist of the highest ranked commons

The state graph of the system of Fig 2 1 is shown in Fig 2 2 Such a small system obviously leads to an almost trivial graph. It should be emphasized that a reversal in the direction of the flow of power in a single transmission line or transformer can radically alter the size and shape of this state graph representation of the system Such a reversal can considerably increase or decrease the domain of a generator and hence cause the creation or the disappearance of several commons and links

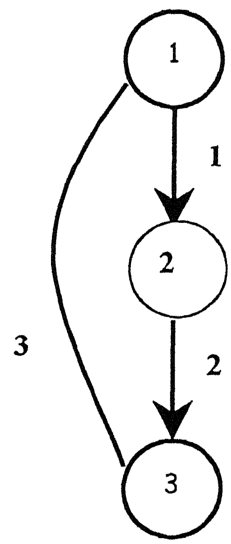

Figure 2.2: State graph for the 6-bus example of figure2 1

Contribution to the load of a common: The results obtained so far provide a qualitative view of the system To obtain quantitative information, a few more definitions and fundamental assumptions are required.

The inflow of a common is defined as the sum of the power injected by sources connected to busses located in this common and of the power imported in this common from other commons by links. This inflow is always positive. For root nodes of the state graph, it includes only the power injected within the common as there are no imports. The outflow of a common is equal to the sum of the power exported through links from

this common to commons of higher rank The inflow of a common is equal to the sum of its outflow and of all the loads connected to the busses comprising the common

Further results are dependent on the following proportionality assumption

For a given common, if the proportion of the inflow which can be traced to generator i is x_i, then the proportion of the outflow which can be traced to generator i is also x_i.

It can easily be shown that the following statement is a corollary or an alternate formulation of the proportionality assumption:

For a given common, if the proportion of the inflow which can be traced to generator i is x_i, the proportion of the load which can be traced to generator i is also x_i

This assumption provides the basis of a recursive method for determining the contribution of each generator to the load in each common. Using the following notations.

C_{ik} : Contribution of generator i to the load and the outflow of common k.

F_{jk} : Flow on the link between commons j and k

F_{ijk} : Flow on the link between commons j and k due to generator i.

I_k . Inflow of common k

G_i . Magnitude of source-generator i.

S_k^g Set of Generators located in common k

then:

$$F_{ijk} = C_{ij} * F_{jk} \qquad \text{. . (2 1)}$$

$$I_k = \sum_j F_{jk} + \sum_{i \in S_k^g} G_i \qquad \text{.. . .(2.2)}$$

$$C_{ik} = \frac{\sum_j F_{ijk}}{I_k} \qquad \text{. . (2 3)}$$

These recursive equations can be used to compute the contribution of each generator to each common if they can be initialized The inflow of the root nodes of the state graph is produced entirely by the generators embedded in these commons. The proportion of the outflow traceable to each of these generators can therefore be readily computed and propagated to common of higher rank

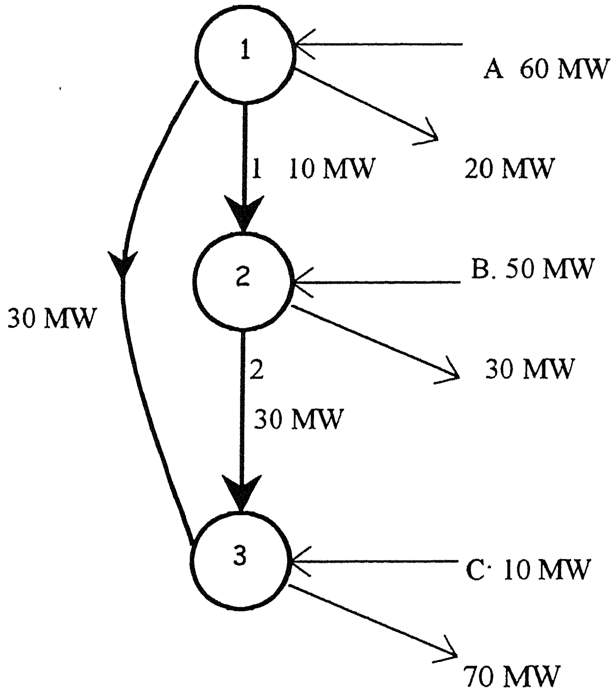

Figure 2.3: Additional load, generation and flow data for the 6-bus example.

(Losses are neglected)

An example based on the system shown in Fig 2 3 is used to explain this procedure. Fig. 2.3 provides additional data about generations, loads in commons and flows on links.

First compute the inflows of each common.

Common 1: 60 MW

Common 2: $50 + 10 = 60$ MW

Common 3: $10 + 30 + 30 = 70$ MW

Then, compute the contributions starting from the root node of the state graph:

Relative contribution to the load and outflow of common 1:

Generator A· $60/60 = 1.0$ p.u.

Absolute contributions to the inflow of common 2

Generator A 10 * 1 0 = 10 MW

Generator B 50 MW

Relative contributions to the load and outflow of common 2

Generator A 10/60 = 0 167 p u

Generator B 50/60 = 0.833 p u.

Absolute contributions to the inflow of common 3

Generator A 30 * 1.0 + 30 * 0 167 = 35 MW

Generator B. 30 * 0.833 = 25 MW

Generator C 10 MW

Relative contributions to the load of common 3 (and to its outflow if there was any).

Generator A 35/70 = 0 5 p.u.

Generator B 25/70 = 0.357 p.u

Generator C. 10/70 = 0 143 p u.

In other words, it is now possible to conclude that generator A produces 50% of the load consumed in common 3 but only 16 7% of the load consumed in common 2.

Contributions to individual load and branch flows:

Considering that all busses within a common are indistinguishable from each other as far as power tracing is concerned, it is reasonable to apply the proportionality assumption not only to the common taken as a whole but also to each bus load and to each branch flow taken independently within the common In other words, if x_{ij} is the contribution of generator i to common j, it is also the contribution of generator i to every bus load and to every branch flow within common j and to every branch flow in the outward links of common j.

Knowing the common to which a bus belong and the contribution of each generator to each common, therefore, gives the ability to compute how much power each generator contributes to each load It also makes it possible to compute what proportion of the use of each branch can be apportioned to each generator. For branches linking busses in separate commons, the proportion of usage should be based on the contribution of the generator to the lower ranked common

Since it is reasonable to assume that generators contribute to the losses in a branch in proportion to their use of this branch, it is possible to compute what proportion of the output of generator is dissipated in losses in the system

2.3 Tracing Real Power Flow

By applying the above method to real power flow obtained by running load flow program, real power can be traced. First the domain of the real power sources are determined. Using these domains, commons are obtained which are group of contiguous busses and are supplied by same generators The real power flows in the links between the commons and inflows to each common are then determined. Contribution factor of generators to each commons can be determined by using the recursive equations (2 1, 2.2, 2.3). By applying proportionality assumption, proportion of the use of each branch can be apportioned to each generator

2.4 Tracing Reactive Power Flow

Starting from a base power flow solution, all active and reactive injections and line flows obtained from this solution are translated into complex currents as expressed in [15]. Injections are represented as sources or sinks of real and imaginary currents Following facts are considered in the algorithm·

1. Generators are sources of real current but may be sources or sinks of imaginary currents depending on their power factor and the sign of their voltage angle.
2. Loads are sinks of real current but may be either sources or sinks of imaginary current.
3. Shunt reactors and capacitors are normally sinks and sources of imaginary currents, respectively. They are also either sources or sinks of real current unless they are connected to the reference bus.
4. The shunt capacitances of the Π model of a transmission line must be included in the real and imaginary sources or sinks located at the busses where the line terminates. Failure to include these capacitances would make the results erroneous, particularly at the light loads.

While one could offset current sinks against current source at each bus, it seems preferable to maintain their individuality A bus to which both generation and load are

connected could, therefore, be home to both real and imaginary current sources as well as both real and imaginary current sinks To obtain an exact balance of real and imaginary currents, it is essential that the injections corresponding to the equivalent shunt admittances of all branches be included in these sources and sinks

Since the real and imaginary components of the current are orthogonal, Kirchoff's current law applies to each of them separately No physical device can transform a real current into an imaginary current or vice-versa For a given power flow solution, real and imaginary currents are, therefore, totally decoupled For the purpose of analysing flows between current sources and current sinks, the actual network can be treated as the conjunction of two separate networks The real current network connects the real current sources to the real current sinks and its branches carry only the real component of the branch currents Similarly, the imaginary current network carries the imaginary component of the branch current from the imaginary current sources to the imaginary current sinks

Applying the concept and algorithm explained in section 2.2, the domain of real current sources and imaginary current sources can be determined A bus usually belongs to the domain of several real current sources and to the domain of several imaginary current sources After this the sets of contiguous buses which are supplied by the same sources can be determined Such buses form a source common It should be noted that each bus belongs to one and only one real source common and to one and only one imaginary source common Now state graph can be formed It is to be noted that the state graph for the real currents is usually quite different from the state graph for the imaginary currents. In order to trace the amount of current flowing from a source to the various sinks in the domain, the above mentioned proportionality assumption is applied

Sink current contributions from source currents:

The computation of the contributions starts from the root nodes of the state graph where the contribution of the local sources is 100% As it then proceeds layer by layer towards the leaf nodes, it is governed by the following equations:

$$I_k^n = \sum_{j \in \phi_k^n} F_{jk}^n + \sum_{i \in \psi_k^n} S_i^n \qquad \ldots (2.4)$$

$$F_{ijk}^{n} = C_{ij}^{n} * F_{jk}^{n} \qquad (2\ 5)$$

$$C_{ik}^{n} = \frac{\sum_{j \in \psi_k^n} F_{ijk}^{n}}{I_k^n} \qquad \text{If source i is not in common k} \qquad (2\ 6)$$

$$C_{ik}^{n} = \frac{S_i^n}{I_k^n} \qquad \text{If source i is in common k} \qquad (2\ 7)$$

where.

I_k^n Inflow of common 'k'

S_i^n . Magnitude of source i

ϕ_k^n Set of commons located upstream from common k in the state graph

ψ_k^n . Set of sources located in common k

F_{jk}^n : Current on the link between commons j and k

F_{ijk}^n : Current between commons j and k due to source i

C_{ij}^n Contribution of source i to common j

The superscript n takes the value x or y depending on whether real or imaginary contributions are being calculated.

These recursive equations can be used to compute the contribution of each current sources to each common if they can be initialized Fortunately, the inflows of the root nodes of the state graph are produced entirely by the current sources embedded in these commons The proportion of the outflow traceable to each of these current sources can therefore be readily computed and propagated to commons of higher rank.

Contributions to individual loads and branch flows:

By using above equations, the contribution of real and imaginary current sources can be calculated separately to the commons and by applying proportionality assumption not only to the common taken as whole, but also to each bus load and to each branch flow taken independently within the common Contribution factor of real power generations to each common is same as the contribution factor of real current sources, in same way

contribution factor of reactive power generations to each common is same as the contribution factor of imaginary current sources

2.5 Study Results

The study has been conducted on the IEEE-14 bus and IEEE-30 bus test systems, slightly modified to represent deregulated market situation The details of these systems are given in the Appendix –A and B, respectively The losses are assumed to be supplied, only by the slack generator at bus #1 in both the systems.

2.5.1 IEEE-14 bus test system

Figure 2.4 shows the modified IEEE-14 bus test system. This system has three real power generators and two synchronous condensor. It has 20 lines The generators and loads data including the MVAR limits of the generators, are shown in Table A.1. Transformer and line data are provided in Table A 2 and A.3, respectively Bus-1 is chosen as slack bus.

2.5.1.1 Tracing real power

Real power tracing has been first carried out using procedure as described in ref [26]. Table 2.1 and 2.2 give the active power generation, load and line flow data (after running load flow)

Table 2.1 Active power generations and loads (IEEE-14 bus system)

Bus no	Generation (MW)	Load (MW)
1	97 67	0
2	159	21.7
3	100	11.2
4	0.00	94.2
5	0.00	0.00
6	0.00	0.00
7	0.00	29 5
8	0.00	7.60
9	0.00	47.8
10	0.00	9.00
11	0.00	50.0
12	0.00	6.10
13	0.00	50.0
14	0.00	14 9

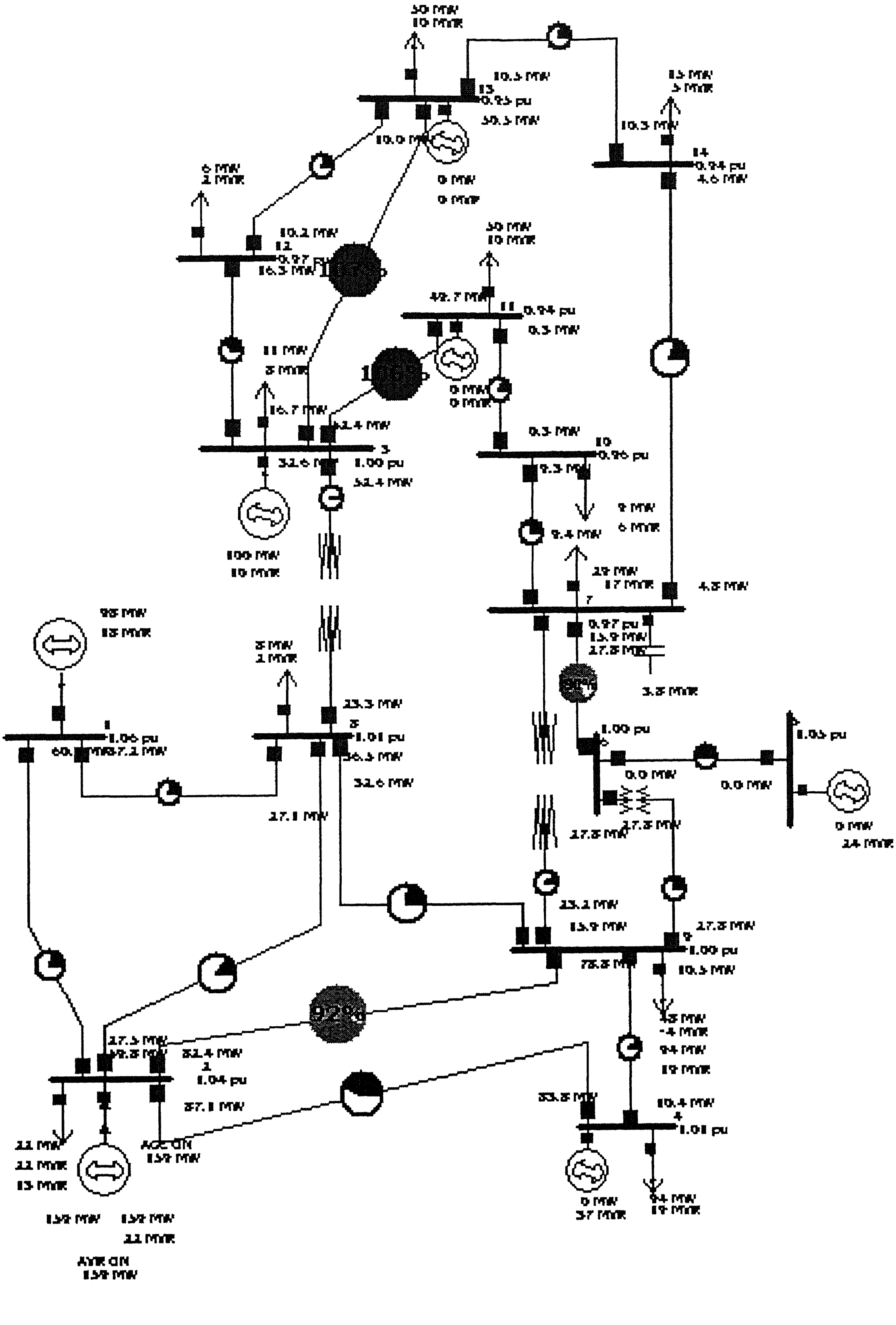

Figure 2.4:IEEE 14-Bus Test System

Table 2 2 Active power flows in the branches (IEEE-14 bus system)

From bus	To bus	Flow (MW)
2	1	-59 8
1	8	37 2
2	4	87.1
2	8	27 5
2	9	82 4
8	3	32.6
3	11	52.4
3	12	16.7
3	13	52.4
4	9	-10 4
6	5	0 0
6	7	27.8
9	6	27.8
9	7	15.9
7	10	9 4
7	14	4 8
9	8	-23.2
10	11	0.3
12	13	10.2
13	14	10 5

First the domain of three generators were calculated which is shown in Table 2 3

Table 2 3 Domain of the generators for the IEEE-14 bus system

Generator bus no	Domain
1	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
2	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
3	3, 11, 12, 13, 14

It can be noted that the size of these domains varies between 5 busses for the generator 3 and 14 buses (whole system) for generator 1

Having established the domains, it is now possible to determine the commons These are shown in Table 2 4

Table 2.4· Common of the IEEE 14-bus system

Common no	Bus no
1	1
2	2, 4, 8, 9
3	3, 11, 12, 13, 14
4	5, 6, 7, 10

Common 1 is supplied by generator 1 only, common 2 by generators 1 and 2 both, common 3 by all three generators and common 4 by generator 1 and 2 both Common 2 and 4 are treated as separate commons because they are unconnected

Figure 2.5 shows how these commons and links form a directed, acyclic state graph

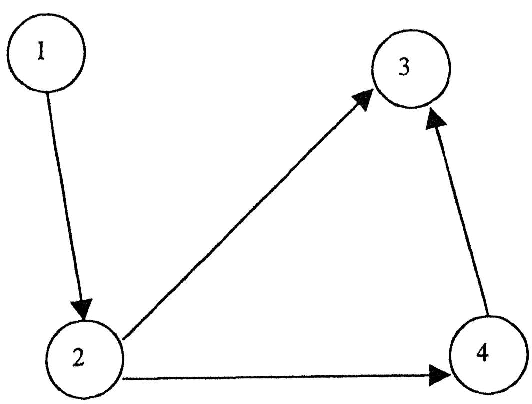

Figure2.5: State graph of the IEEE 14-bus system

Using the information contained in Tables 2 1 and Table 2 2, it is possible to compute the flows on each of the links and inflows to each common. Table 2.5 shows flows on links between commons and Table 2 6 shows inflows to each commons

Table 2 5 Flows (MW) on the links between commons of the IEEE-14 bus system

Common no	1	2	3	4
1	0	97 0	0	0
2	0	0	32.6	43 7
3	0	0	0	0
4	0	0	5 1	0

Table 2 6: Inflows to commons of the IEEE 14-bus system

Common no	Inflow (MW)
1	97 67
2	256 0
3	137 7
4	43 7

From Table 2.5, flow on the link between common #1 and #2 is 97 MW Similarly flow on link between common #2 and #3 is 32.6 MW From table 2 6, inflow to common 1 is 97.67 MW.

Starting from the root nodes of the state graph and moving towards the leave nodes, it is finally possible to compute the contributions of the generators to each of the commons. These contributions are summarized in the Table 2 7

Table 2 7 Contribution factors of the generators to the commons

(IEEE14-bus system)

Gen bus no	Common no			
	1	2	3	4
1	1 0000	0.3789	0 1037	0 3789
2	0 0000	0.6211	0 1700	0.6211
3	0 0000	0.0000	0.7262	0 0000

The non-zero element in the Table 2.7 shows how much "power mixing" takes place in the system at a particular time. Contribution factor of generator 1 to common 1 is 1.0, to common 2 is 0 3789, to common 3 is 0 1037 and to common 4 is 0.3789. It means that the generator 1 is responsible for 10.37% of flow on the line between 3 and 11. It is also seen that for commons where power mixing takes place, the contributions vary from almost 100% to almost zero.

Tracing real power as described in ref. [15], Contribution factors of the real current sources to each common are computed. These contribution factors are summarized in the Table 2 8

The real generation contribution factors to the commons as obtained by using real power flow in the lines are shown in Table 2.7, which are approximately same as that obtained by using current flow in lines as described in ref. [15], shown in Table 2.8.

Table 2.8: Contribution factors of the real current sources to the commons

(IEEE 14-bus system)

Gen bus no	Common no			
	1	2	3	4
1	1.0000	0.3778	0.0943	0 3778
2	0 0000	0.6222	0.1553	0.6222
3	0.0000	0.0000	0.7504	0 0000

2.5.1.2 Tracing reactive power

Table 2 9 presents the current flow in the branches Table 2 10 gives the imaginary current sources at buses, Table 2.11 give the voltage of the buses, Table 2.12 give the real and reactive power generations.

Table 2 9· Current flow in the branches (IEEE-14 bus system)

Form bus	To bus	Line current (p.u)
8	3	0.2383 - 0 0725i
9	6	0 2442 - 0 0028i
9	7	0.1278 - 0 0671i
1	8	0 3084 - 0 1453i
2	8	0 2323 - 0 1178i
4	9	-0.1386 - 0.0952i
9	8	-2.2164 - 0.1054i
1	2	0 4926 - 0.0982i
2	4	0.8169 - 0 0681i
6	5	0.0471 + 0 2243i
2	9	0.7563 - 0 0846i
6	7	0.1820 - 0 3337i
7	10	0.0225 - 0 1636i
3	11	0.4864 - 0 1210i
3	12	0.1544 - 0 0394i
3	13	0 4735 - 0 1642i
7	14	0.0126 - 0 0960i
10	11	-0.0541 - 0.0832i
12	13	0.0953 - 0 0131i
13	14	0.1285 + 0.0085i

Table 2 10 Imaginary current sources (IEEE-14 bus system)

Bus no	Imaginary current sources (p.u)
1	0 1899
2	0 1719
3	0 0619
4	0.3503
5	0.2292

Table 2.11: Voltage data of busses (IEEE-14 bus system)

Bus no	Bus voltage (p.u)
1	1 0600
2	1.0446 - 0 0272i
3	0 9927 - 0 1210i
4	0.9928 - 0 1858i
5	1 0247 - 0 2150i
6	0.9852 - 0.2067i
7	0.9485 - 0 2268i
8	1.0109 - 0 0609i
9	0 9858 - 0 1557i
10	0 9339 - 0.2235i
11	0 9224 - 0.2062i
12	0 9636 - 0 1556i
13	0.9399 - 0 1718i
14	0.9209 - 0.2180i

Table 2 12 Active and reactive power generation at buses
(IEEE 14-bus system)

Bus no	Real generation (MW)	Reactive generation (MVAR)
1	114.53	20.13
2	159.00	17.96
3	100.00	6.19
4	0 00	35.18
5	0 00	24.00
6	0.00	0.00
7	0 00	0 00
8	0.00	0.00
9	0.00	0 00
10	0 00	0.00
11	0.00	0 00
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00

Tracing the imaginary current, first the domains of imaginary current sources are calculated which are shown in Table 2 13 Having determined the domains of all the imaginary current sources and using algorithm explained in section 2.2, commons were determined which are the sets of the contiguous buses supplied by the same sources. Table 2.14 shows the commons. Figure 2 6 shows how these commons and links form directed, acyclic state graph

Using the information contained in Tables 2.9 and 2.11, it is possible to compute the imaginary current on each of the links and inflows to each common. Table 2.15 shows imaginary current on links between commons and Table 2.16 shows inflows to each commons.

Table 2 13. Domain of the imaginary current sources for the IEEE 14-bus example

Imaginary current sources	Domain
1	1, 2, 3, 4, 6, 7,8, 9, 10, 11, 12, 13, 14
2	2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14
3	3, 11, 12, 13
4	3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14
5	5, 6, 7, 10, 11, 13, 14

Table 2.14· Reactive commons for the IEEE 14-bus system

Common no	Bus no
1	1
2	2
3	3, 12
4	4, 9
5	5
6	6, 7, 10, 14
7	8
8	11
9	13

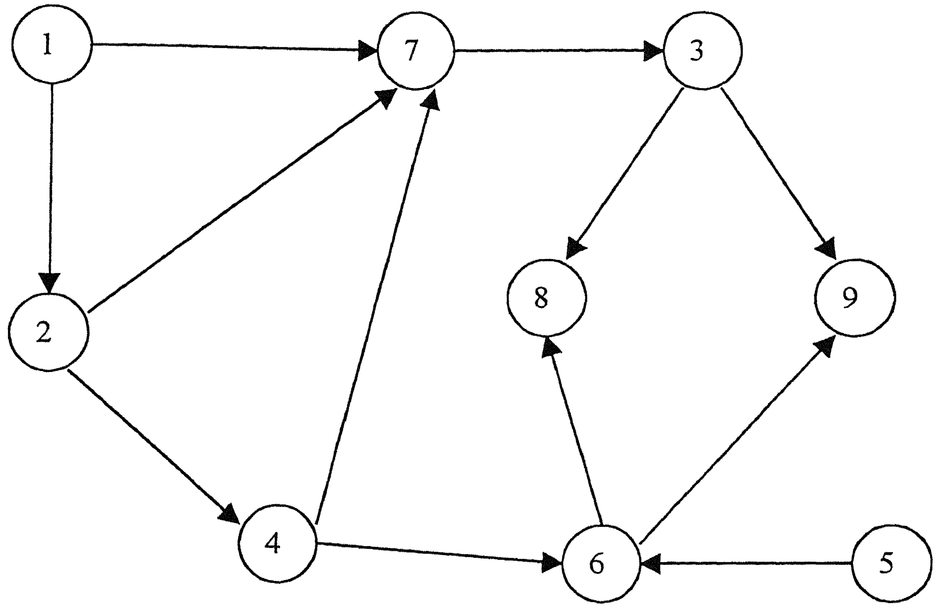

Figure2.6 State graph for the IEEE 14-bus system

Table 2 15· Imaginary current on the links between commons for the IEEE 14-bus system

Common no	1	2	3	4	5	6	7	8	9
1	0.0	0.0982	0.0	0.0	0.0	0 0	0.145	0.0	0.0
2	0.0	0.0	0.0	0.1527	0.0	0.0	0.118	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0 0	0.121	0 177
4	0.0	0.0	0.0	0.0	0.0	0.0698	0.105	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0 2243	0.0	0.0	0.0
6	0.0	0.0	0.0	0 0	0.0	0.0	0.0	0.083	.0085
7	0.0	0.0	0.0725	0.0	0.0	0.0	0 0	0.0	0.0
8	0.0	0.0	0.0	0 0	0 0	0 0	0 0	0 0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2 16· Inflow to each common (IEEE-14 bus system)

Common no	Inflow (p u)
1	0 1899
2	0 2700
3	0 1344
4	0 5030
5	0 2292
6	0 2941
7	0.3684
8	0 2042
9	0.1858

Starting from the root nodes of the state graph and moving towards the leave nodes, it is finally possible to compute the contribution factors of the imaginary current source to each of the commons. These contribution factors are summarized in the Table 2.17

Table 2.17: Contribution factors of the imaginary current sources to the commons of the 14-bus system

Imaginary current sources	Common no								
	1	2	3	4	5	6	7	8	9
1	1.0	.3635	.2924	.1104	0.0	0262	.5421	.1839	.2803
2	0.0	.6365	.1396	.1932	0 0	.0459	.2587	.1014	.1353
3	0.0	0.0	.4606	0 0	0 0	0.0	0.0	.2729	.4396
4	0.0	0.0	.1075	6964	0 0	1654	.1992	.1311	.1101
5	0.0	0.0	0.0	0.0	1 0	.7625	0.0	.3108	.0347

The reactive generation contribution factors to the commons are the same as the contribution factors for imaginary current sources By applying proportionality assumption, the reactive power flow to each branches of the system can be traced

2.5.2 IEEE-30 Bus Test System

Figure 2.7 shows the modified IEEE-30 bus test system. This system has six real power generators and 41 lines The generators and loads data including the MVAR limits of the generators are shown in the Table B 1 Transformer and line data are provided in the Table B.2 and B.3, respectively. Bus-1 is chosen as slack bus.

2.5.2.1 Tracing real power

Real power tracing has been first carried out using procedure as described in ref [26]. Table 2.18 and 2.19 give the active power generation, load and line flow data (after running load flow).

First the domain of six generators were calculated which is shown in Table 2 20 Having established the domains, it is now possible to determine the commons These are shown in Table 2.21. Figure 2 8 shows how these commons and links form a directed, acyclic state graph.

Using the information contained in tables 2 18 and 2.20, it is then possible to compute the flows on each links and inflows to each common. Table 2.22 shows flows on links between commons and Table 2.23 shows inflows to each commons

Starting from the root nodes of the state graph and moving towards the leave nodes it is finally possible to compute the contributions of the generators to each of the commons. These contributions are summarized in the Table 2.24.

Table 2 18· Active power generations and loads (IEEE-30 bus system)

Bus no	Real generation (MW)	Reactive generation (MW)
1	119.45	8.35
2	40 00	40 00
3	00.00	0 00
4	00.00	0.00
5	31 00	21 94
6	00.00	0.00
7	00.00	0.00
8	50.00	40 00
9	00.00	0.00
10	00.00	0.00
11	50.00	7.47
12	00.00	0.00
13	50.00	22.85
14	00.00	0.00
15	00.00	0.00
16	00.00	0 00
17	00.00	0.00
18	00.00	0.00
19	00.00	0.00
20	00.00	0 00
21	00.00	0.00
22	00.00	0 00
23	00.00	0 00
24	00.00	0 00
25	00.00	0 00
26	00.00	0 00
27	00.00	0.00
28	00.00	0 00
29	00 00	0.00
30	00.00	0.00

Table 2.19 Active power flows in the branches (IEEE-30 bus system)

From Bus	To Bus	Real Flow (MW)
1	2	67 8
1	3	51 7
2	4	41 4
2	5	22.8
2	6	42.8
3	4	38 5
4	6	8 3
4	12	30 3
5	7	22.5
6	7	-2 2
6	8	-11 8
6	9	-28 8
6	10	16 5
6	28	18.7
8	28	8.2
10	9	-28.8
9	11	-50.0
10	17	3.6
10	20	10.6
10	21	16.9
10	22	8.4
12	13	-50.0
12	14	30 4
12	15	30.8
12	16	9 1
14	15	-10.9
15	18	5.0
15	23	5 1
16	17	5.5
18	19	1 6
19	20	-7.9
21	22	-0.7
22	24	7.6
23	24	1.8
24	25	0.6
25	26	3.5
25	27	-2.9
28	27	26.8
27	29	13.6
27	30	10.2
29	30	1.1

Table 2.20 Domain of the generators for the IEEE 30-bus system

Gen bus no	Domain
1	1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30
2	2, 4, 5, 6, 7, 9, 10, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30
5	5, 6, 7, 9, 10, 17, 19, 20, 21, 22, 24, 25, 26, 27, 28, 29, 30
8	6, 8, 9, 10, 17, 19, 20, 21, 22, 24, 25, 26, 27, 28, 29, 30
11	9, 10, 11, 17, 19, 20, 21, 22, 24, 25, 26
13	12, 13, 14, 15, 16, 17, 18, 19, 23, 24, 25, 26

Table 2.21. Common for the IEEE-30-bus system

Common no	Bus no
1	1, 3
2	2, 4
3	5, 7
4	6, 28
5	8
6	9, 10, 20, 21, 22
7	11
8	12, 14, 15, 16, 18, 23
9	13
10	17
11	19
12	24, 25,26
13	27, 29, 30

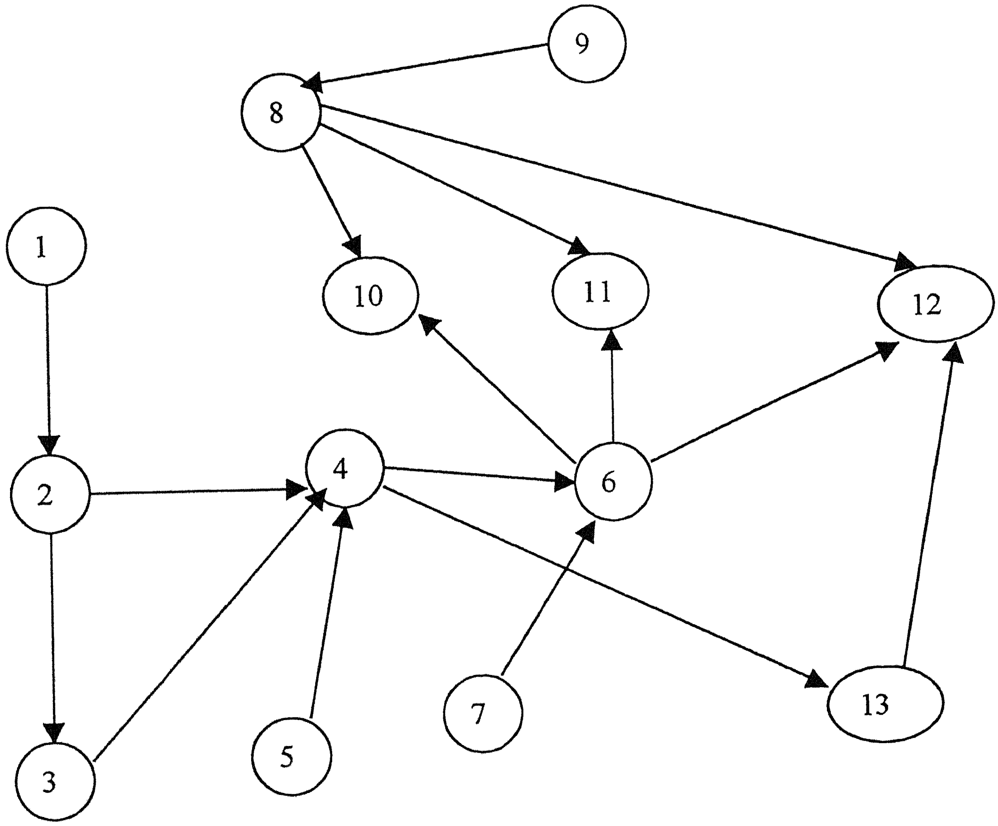

Figure2.8: State graph for the IEEE 30-bus system

Table 2 22: Flows (MW) on the links between commons for the IEEE 30-bus system

Com mon no	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0.0	106	0.0	0 0	0 0	0.0	0.0	0 0	0 0	0 0	0.0	0.0	0.0
2	0.0	0 0	22.8	51.1	0.0	0.0	0.0	30 3	0.0	0.0	0.0	0.0	0 0
3	0.0	0.0	0.0	2 2	0.0	0 0	0 0	0 0	0.0	0 0	0.0	0.0	0.0
4	0 0	0.0	0.0	0 0	0.0	45.3	0.0	0 0	0 0	0.0	0 0	0.0	26.8
5	0.0	0 0	0.0	20	0.0	0.0	0.0	0 0	0.0	0 0	0.0	0.0	0.0
6	0.0	0.0	0 0	0.0	0.0	0.0	0 0	0 0	0 0	3 6	7 9	7.6	0 0
7	0.0	0.0	0.0	0.0	0.0	50.0	0.0	0.0	0.0	0 0	0 0	0.0	0 0
8	0.0	0.0	0.0	0.0	0.0	0 0	0.0	0.0	0.0	5 5	1 6	1 8	0 0
9	0.0	0 0	0.0	0.0	0.0	0 0	0.0	50 0	0.0	0 0	0.0	0.0	0 0
10	0.0	0 0	0.0	0.0	0.0	0 0	0.0	0.0	0.0	0 0	0.0	0 0	0 0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0 0	0 0	0 0	0 0	0 0	0.0	0.0	0 0	0 0	0 0	0 0	0 0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0 0	0 0	2.9	0 0

Table 2.23. Inflows to each commons for the IEEE 30-bus system

Common no.	Inflow (MW)
1	119 45
2	146 3
3	53 8
4	73 3
5	50.0
6	95.3
7	50.0
8	80.3
9	50.0
10	9.1
11	9.5
12	12 3
13	26 8

Table 2.24· Contribution factors of the generators to the commons (IEEE 30-bus system)

Gen bus no	Common no												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1 0	.727	.308	.516	0 0	245	0 0	274	0.0	263	.250	313	516
2	0 0	273	.116	.194	0 0	.092	0 0	.103	0.0	099	.094	.118	194
5	0 0	0.0	.576	017	0 0	.008	0.0	0.0	0 0	003	.007	009	.017
8	0.0	0.0	0 0	.273	1 0	129	0 0	0.0	0.0	.051	.108	145	.273
11	0.0	0.0	0 0	0.0	0.0	.525	1 0	0.0	0.0	208	436	324	0 0
13	0.0	0.0	0.0	0.0	0.0	0.0	0 0	623	1.0	.376	105	091	0 0

Tracing real power as described in ref. [15], Contribution factors of the real current sources to each common are computed These contribution factors are summarized in the Table 2 25.

The real generation contribution factors to the commons as obtained by using real power flow in the lines are shown in Table 2 24, which are approximately same as that obtained by using current flow in lines as described in ref [15], shown in Table 2 25.

Table 2.25: Contribution factors of the real current sources to the commons of the IEEE 30-bus system

Gen. bus no	Common no												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1.0	.725	.297	.516	0.0	.249	0 0	278	0.0	.268	.261	.304	.516
2	0.0	.275	.113	.195	0 0	.095	0 0	.105	0.0	.102	099	115	.195
5	0.0	0.0	.590	.022	0.0	011	0.0	0.0	0.0	.004	.006	012	022
8	0.0	0.0	0.0	.267	1 0	129	0 0	0 0	0.0	046	077	144	267
11	0.0	0.0	0.0	0.0	0.0	.516	1.0	0 0	0.0	182	.308	369	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.617	1.0	.399	248	.056	0 0

2.5.2.2 Tracing reactive power

Table 2 26 gives the current flow in the branches Table 2 27 gives the voltage of the buses, Table 2.28 gives the imaginary current sources at buses and Table 2.29 gives the real and reactive power generations.

Tracing the imaginary current, first the domains of imaginary current sources are calculated which are shown in Table 2 30 Having determined the domains of all the imaginary current sources and using algorithm explained in section 2.2, commons were determined which are the sets of the contiguous buses supplied by the same sources Table 2.31 shows the commons. Figure 2.9 shows how these commons and links form directed, acyclic state graph.

Using the information contained in Tables 2.26 and 2.27, it is possible to compute the imaginary current on each of the links and inflows to each common. Table 2.32 shows imaginary current on links between commons and Table 2.33 shows inflows to each commons.

Starting from the root nodes of the state graph and moving towards the leave nodes, it is finally possible to compute the contribution factors of the imaginary current source to each of the commons. These contribution factors are summarized in the Table 2 34.

Table 2.26· Current flow in the branches (IEEE-30 bus system)

From bus	To bus	Line current (p.u)
1	2	0.4854 - 0.0183i
1	3	0 4026 - 0 1523i
2	4	0.3310 - 0 1552i
3	4	0.2810 - 0.1608i
2	5	0 1842 - 0 1639i
2	6	0 3421 - 0 1614i
4	6	0 0669 - 0.0412i
5	7	0 1905 - 0 0359i
6	7	0.0023 - 0.0700i
6	8	-0.1155 + 0.1014i
6	9	0 2300 - 0.0061i
6	10	0.1292 - 0.0308i
9	11	-0.4769 + 0.1905i
9	10	0.2180 - 0.1443i
4	12	0 1625 + 0.0458i
12	13	-0.4643 + 0 2518i
12	14	0.1624 - 0.1099i
12	15	0.2293 - 0.3162i
12	16	0 1154 - 0.0543i
14	15	-0.0222 - 0 0662i
16	17	0.0828 - 0 0319i
15	18	0.0656 - 0.1380i
18	19	0 0624 + 0.0904i
19	20	-0.0272 + 0 1689i
10	20	0.0502 - 0.1791i
10	17	-0 0012 - 0.0394i
10	21	0.1423 - 0.1240i
10	22	0.0687 - 0.0577i
21	22	-0.0186 + 0 0162i
15	23	0 0890 + 0.0027i
22	24	0.0511 - 0.0413i
23	24	0 0376 + 0.0424i
24	25	0.0260 + 0 0246i
25	26	0.0316 - 0.0303i
25	27	-0 0056 + 0.0549i
28	27	0.2321 - 0.0549i
27	29	0.1238 - 0.0450i
27	30	0.0954 - 0.0377i
29	30	0.0134 - 0.0092i
8	28	0.0729 - 0.0403i
6	28	0 1604 - 0.0725i

Table 2 27· Voltage data of busses (IEEE-30 bus system)

Bus no	Bus voltage (p.u)
1	1.0600
2	1 0496 - 0 0276i
3	1 0136 - 0 0677i
4	1 0038 - 0 0762i
5	1 0084 - 0 0564i
6	1 0013 - 0 0785i
7	0 9955 - 0 0768i
8	1 0069 - 0 0749i
9	1 0000 - 0 1263i
10	0.9841 - 0 1503i
11	1 0396 - 0.0271i
12	1 0155 - 0 1178i
13	1.0508 - 0.0528i
14	0 9674 - 0.1458i
15	0.9591 - 0 1268i
16	0.9938 - 0.1356i
17	0.9809 - 0 1489i
18	0 9219 - 0.1263i
19	0 9296 - 0 1401i
20	0.9420 - 0.1440i
21	0 9699 - 0.1566i
22	0 9705 - 0.1564i
23	0.9507 - 0.1450i
24	0 9572 - 0 1608i
25	0.9604 - 0.1740i
26	0.9409 - 0.1783i
27	0 9725 - 0.1788i
28	0.9942 - 0 0869i
29	0 9266 - 0.2203i
30	0.9192 - 0.2242i

Table 2.28: Imaginary current sources (IEEE-30 bus system)

Bus no	Imaginary current sources (p.u)
1	0 1149
2	0.3555
5	0.0276
8	0.3961
11	0.1779
13	0.2281

Table 2.29 Active and reactive power generation at buses (IEEE-30 bus system)

Bus no	Real generation (MW)	Reactive generation (MVAR)
1	94 04	12.18
2	40.00	37.33
3	00.00	00.00
4	00.00	00.00
5	31 00	2.79
6	00.00	00.00
7	00.00	00.00
8	50.00	40.00
9	00.00	00.00
10	00.00	00.00
11	50 00	18.50
12	00.00	00.00
13	50.00	24.00
14	00 00	00.00
15	00.00	00.00
16	00.00	00.00
17	00.00	00.00
18	00 00	00.00
19	00 00	00.00
20	00.00	00.00
21	00 00	00.00
22	00.00	00.00
23	00.00	00.00
24	00.00	00.00
25	00.00	00.00
26	00.00	00.00
27	00.00	00.00
28	00.00	00.00
29	1.59	8.31
30	00.00	00 00

Table 2 30 Domain of the imaginary current sources for the IEEE 30-bus system

Imaginary current sources	Domain
1	1, 2, 3, 4, 5, 6, 7, 9, 10, 15, 17, 18, 19, 20,21, 22, 23, 24, 25, 26, 27, 28, 29, 30
2	2, 4, 5, 6, 7, 9, 10, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30
5	5, 7
8	6, 7, 8, 9, 10, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30
11	9, 10, 11, 15, 17, 18, 19, 20, 21, 22, 23, 24
13	4, 6, 7, 9, 10, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30

Table 2.31. Reactive commons for the IEEE 30-bus system

Common no	Bus no
1	1, 3
2	2
3	4
4	5
5	6, 28
6	7
7	8
8	9, 10, 17, 20, 21, 22, 24
9	11
10	12, 13, 14, 16
11	15, 18, 19, 23
12	25, 26, 27, 29, 30

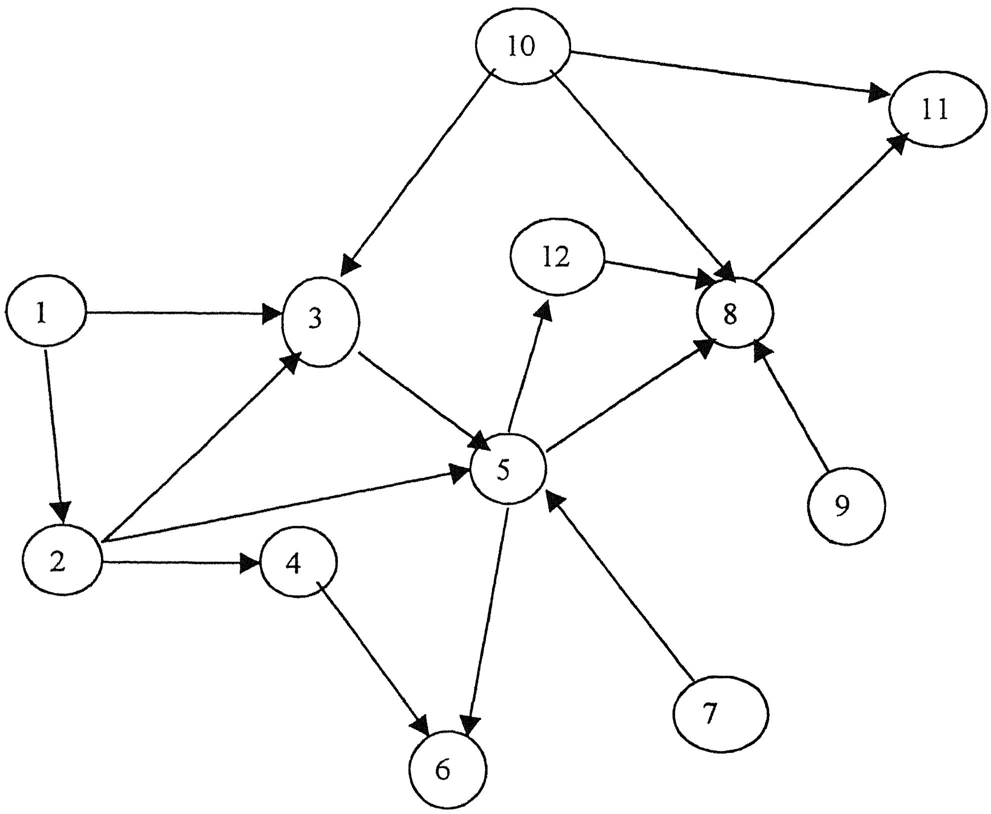

Figure2.9: State graph for the 30-bus system

Table 2.32. Imaginary current (p.u) on the links between commons of the (IEEE-30 bus system)

Com-mon no	1	2	3	4	5	6	7	8	9	10	11	12
1	0.0	.018	.161	0 0	0.0	0.0	0.0	0 0	0.0	0 0	0.0	0.0
2	0 0	0.0	155	.164	.161	0.0	0 0	0 0	0.0	0.0	0 0	0.0
3	0.0	0.0	0.0	0.0	.041	0.0	0 0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	.036	0.0	0.0	0.0	0.0	0.0	0 0
5	0.0	0.0	0.0	0.0	0.0	0.07	0.0	.037	0.0	0.0	0.0	.055
6	0.0	0.0	0.0	0.0	0.0	0 0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	.142	0.0	0.0	0.0	0 0	0.0	0 0	0 0
8	0.0	0.0	0.0	0 0	0.0	0.0	0.0	0.0	0.0	0.0	.211	0 0
9	0 0	0.0	0.0	0.0	0 0	0.0	0 0	191	0 0	0.0	0.0	0.0
10	0.0	0.0	.046	0.0	0 0	0.0	0 0	.032	0.0	0.0	.382	0.0
11	0.0	0.0	0.0	0.0	0 0	0.0	0.0	0.0	0.0	0 0	0 0	0.0
12	0.0	0.0	0.0	0 0	0 0	0.0	0 0	.025	0 0	0 0	0.0	0.0

Table 2 33 Inflow to each common (IEEE 30-bus system)

Common no	Inflow (p u)
1	0 1149
2	0 3738
3	0 3617
4	0 1915
5	0 3443
6	0.1058
7	0 3961
8	0 2840
9	0 1779
10	0.2281
11	0 5937
12	0 0549

Table 2.34: Contribution factors of the imaginary current sources to the commons (IEEE 30-bus system)

Imaginary current sources	Common no											
	1	2	3	4	5	6	7	8	9	10	11	12
1	1.0	.049	.465	.042	.079	.066	0.0	017	0.0	0.0	.006	.079
2	0.0	.951	.408	.814	.495	.603	0 0	107	0.0	0.0	038	495
5	0.0	0 0	0.0	144	0.0	.049	0 0	0 0	0.0	0.0	0.0	0 0
8	0.0	0.0	0.0	0.0	.412	.272	1.0	089	0 0	0 0	.032	.412
11	0.0	0.0	0.0	0.0	0 0	0.0	0 0	.671	1 0	0 0	239	0 0
13	0.0	0.0	.127	0.0	.015	0.01	0 0	.116	0.0	1.0	685	015

2.6 Conclusions

This chapter has presented algorithm and concepts for tracing active and reactive power The proposed methods are simple for tracing power in deregulated market by calculating the contribution of each generator to a given load or to the flow in a line. The studies have been conducted on IEEE-14 and IEEE-30 bus systems. From the results obtained, following main conclusions can be drawn

1 The proposed method is applicable to both active and reactive power tracing But in the case of reactive power tracing, all power injections are translated into real and imaginary currents The method then traces these currents to determine contribution of each imaginary current source which are in turn same as the contribution of the reactive power sources
2. It is seen that the domain and common might be different for the real and reactive sources for the same system.
3. The contribution of generators to line flows, in case of active power tracing, is same as those obtained by considering real power or complex current flow in lines.

This method can be used to resolve some of the difficult issues of the deregulated market such as pricing and congestion cost management. In competitive environment this method will be useful in ensuring fairness and transparency in the operation of the electricity supply systems.

Chapter 3

Allocation of Congestion Relief and Voltage Regulation Costs

3.1 Introduction

Under open access, the market driven transactions have become the new independent decision variables for real time power system operation. Whereas in vertically integrated utilities, all the available generators are centrally dispatched, under competition and open access, part of the load may be supplied via privately negotiated bilateral transactions between generators and loads. The remaining load component, if any, may be furnished by the so-called spot market, that is, a pool which dispatches available generation by minimizing the cost of the generation bids in a manner similar to the traditional economic dispatch.

Congestion in a transmission grid occurs due to an operating condition that causes limit violations on one or more of the "flowgates" in the system. The management of congestion has become more important in the deregulated regime as the number and magnitude of power transactions increases. Both the regulating bodies and utilities have recognized the importance of congestion relief as an ancillary service.

Congestion management is especially challenging in a bilateral transaction environment in which individual parties transact power among themselves. One of the approaches to avoid congestion, if it occurs during operation, is to ask the transacting parties to curtail their transactions. This approach is quite conservative in that it leads to inefficient use of the system. In a price based congestion management, the Independent System Operator (ISO) takes an active role in managing the congestion by redispatching the resources based on bids received from the market participants.

One of the important issues in congestion management is the allocation of the congestion cost to the market participants. The cost of relieving congestion should be

allocated in an "equitable" manner among all the market participants The challenge here, is the "equity" i.e., the distribution of the congestion relief cost in proportion to the degree of involvement by each market entity in the congestion Equitable allocation is important in order to get cooperation among market players and also to send the market correct "price signals" for the congestion and thus providing a fair attitude to participants

In ref. [7], the congestion management scheme considered is specially tailored for a bilateral transaction environment. It assumes that the ISO receives all the transaction requests in an hour or a day and makes a congestion assessment study for the given conditions If the analysis indicates some congestion conditions, these conditions are announced to the market participants and the parties are asked to submit bids for redispatch for congestion relief Based on the bids received, the ISO selects the most economic redispatch scenario.

In this work, an OPF routine has been used, which tries to minimize the cost of ancillary generators while relieving the congestion without curtailment of bilateral transactions. The marginal cost of relieving the congestion of a particular line is to be allocated to the generators that are causing the congestion. By using the tracing of real power, the proportionality or line usage by individual generator can be computed. The marginal cost is then allocated to each generator in proportion to their usage

The OPF routine used primarily focuses on managing line congestion. However, the voltages at some buses may violate their limits to meet the transactions. In order to bring the bus voltages with in limit and increase the transmission capacity, shunt compensating devices such as SVC, at optimal locations, are necessary. A shunt compensator has been considered in this work as a reactive power source. The cost of shunt devices is required to be allocated to those generators which are causing the voltage violation in the process of meeting the transactions. By using the reactive power tracing, one can compute the proportion of each generator to the reactive loads at various buses and reactive line flow through each line. Cost of SVC has been allocated to each generator in proportion to which they are supplying the reactive load The studies have been conducted on modified IEEE-14 and IEEE-30 bus systems.

3.2 OPF Formulation taking Congestion Management into Consideration

The purpose of an OPF is to minimize an objective function (cost) by readjusting different system controls taking into account system equality and inequality constraints The OPF has been solved in the past by several optimization methods such as steepest descent method, Newton's method, interior point method, linear programming method, sequential quadratic programming method etc A general mathematical formulation of the OPF can be expressed as:

Minimize an objective function F(x)

subject to equality and inequality constraints,

$h_i(x) = 0 \qquad i = 1, \text{----------}, N_h$

$g_i(x) \geq 0 \qquad I = 1, \text{----------}, N_g$

$x_{i,l} \leq x_i \leq x_{i,h} \qquad I = 1, \text{----------}, N$

where,

N_h · Number of equality constraints

N_g : Number of inequality constraints

x, N: OPF variables and number of OPF variables

OPF package of power world simulator version 6 0 has been used in this work. It uses a linear programming (LP) OPF implementation. The objective function used by the simulator is the sum of the total generation costs Equality constraints are

- Bus MW and MVAR power balance, to represent power flow equations
- Generator voltage set point.

The inequality constraints include

- Generator real power limits.
- Generator reactive power limits.
- Transmission line and transformer (branch) MVA limits

During any constrained minimization, there is always a cost associated with enforcing the equality constraints and the binding inequality constraints. These costs are known as the marginal costs. The successful solution of OPF gives the marginal cost of line/transformer MVA constraint The line/transformer marginal costs indicate incremental cost of enforcing the line or transformer MVA constraint The OPF ensures meeting all the transaction request made by market participants.

3.3 Congestion Management Cost Allocation Using Active Power Tracing

In this section, it is assumed that the total transmission losses are made out of the injected power at bus-1 through a transaction between ISO and a GENCO at this bus The bus-1 has been chosen as the slack bus for the OPF study. The firm power transactions are either bilateral transactions or multilateral transactions

The ancillary generators for congestion management are assumed to be connected at suitable locations in the system. The ancillary generators are initially assumed to provide no generation but provide power to manage congestion if it occurs. The OPF routine has been run to remove the congestion by minimizing the cost of slack generator and ancillary generators. The OPF ensures no curtailment in the bilateral transactions and its output provides marginal cost of relieving the congestion in a particular line.

Since, the marginal cost obtained by running the OPF routine is required to be allocated to the generators that are causing congestion, the active power tracing described in the previous chapter is made use of. The marginal cost of removing congestion is distributed to generators in the proportion of their usage of the lines.

Steps involved in the use of the OPF package for congestion management are as follows:

Step 1: Read system data and create a oneline diagram of the system.

Step 2: Congestion under the desired market transactions, if any, are identified. Using the given loading conditions, run a base case load flow and compute the flows in all the lines.

Step 3: Using the load flow results and the line flows, perform the active power tracing which gives the proportion of use of the lines by each generator.

Step 4 Considering the congestion constraints (line flow constraints) and other constraints, run the optimal power flow (OPF)

Step 5 After the successful solution of OPF, record the marginal cost of removing the congestion

Step 6 Distribute the above marginal cost among generators responsible for congestion in lines in proportion to their usage, obtained in step-3

3.4 Voltage Regulation Cost Allocation Using Reactive Power Tracing

Since, the OPF used in this work primarily focuses on managing line congestion, the voltages at some buses may still remain poor after the OPF run In order to bring these bus voltages within limits, some reactive power source such as SVC is required to be connected at suitable location in the system In the present work SVC has been used for the voltage control purpose in the transmission system. The SVC can be made to generate or absorb reactive power by means of thyristor controlled elements. Here SVC has been considered as a reactive power source with their maximum and minimum limits decided by limiting capacitive and inductive susceptance values Typical value of SVC operating cost is taken from ref. [2].

In this work, to bring the voltage within limits, shunt devices such as SVC are placed at optimal locations and then load flow is run to check whether voltage are brought within limits. The shunt device has been placed at one of the buses where voltage is below acceptable limit. The costs of shunt devices are required to be distributed among generators responsible for voltage violation.

Steps involved in voltage regulation cost allocation are as follows

Step 1: Run the OPF to relieve congestion as explained in section 3.3 and record the buses whose voltages are not within limit.

Step 2: Utilizing the above OPF results and the corresponding line flows, trace the reactive power as described in previous chapter

Step 3: Connect the shunt device (SVC in this work) at one of the buses whose voltages are below acceptable limit.

Step 4 For different MVAR rating of shunt devices run the load flow and stop when all voltages are within limits and record voltages of the bus

Step 5. The cost of shunt device, so selected, is first allocated to those buses where initially voltage violation was recorded In this work the cost has been allocated among these buses, first, in proportion to the change in voltages from the base OPF values (as in step-1)

Step 6· The costs allocated to these buses are then allocated to reactive sources in proportion of their contribution to the reactive power load at these buses as obtained from the reactive power tracing in step-2.

3.5 Study Results

The study has been conducted on the IEEE-14 bus and IEEE-30 bus systems, slightly modified to represent deregulated market situation. The details of these systems are given in the Appendix-A and B, respectively. The losses are assumed to be supplied, only by the generator at bus-1 in both the systems, which is assumed as slack bus

3.5.1 IEEE-14 bus test system

Fig.2.4 shows the modified IEEE-14 bus test system. The generators and loads data including the MVAR limits of the generators are shown in Table A.1. Transformer and line data are provided in Table A 2 and A.3, respectively

3.5.1.1 Congestion management cost allocation using active power tracing

In the IEEE-14 bus system, two groups of bilateral contracts have been considered. Group-1 makes power transfer from bus 2 to buses 4, 9, 8 and 10 and group-2 makes transfers from bus 3 to buses 11 and 13. Table 3 1 presents desired generation and load data of these two groups. Generator at bus-1 is made to supply load at other buses given in Table 3.2 and losses in the system. With these transaction conditions, a load flow was run. The loss to be supplied by generator-1, given in table 3 2, pertains to the base

case load flow The line rating and flow in the lines are shown in Table 3 3 From Table 3.3, it can be observed that the transmission lines between buses 3 & 11 and buses 3 & 13 get overloaded To remove congestion, ancillary generators are connected at buses 13 and 11 They had initially no generation The real power generation limits and cost characteristics of these ancillary generators are given in Table 3 4.

Where cost (f_i) of each of the ancillary generators (say at i^{th} bus) is represented as

$$f_i = \frac{1}{2} a_i P_{Gi}^2 + b_i P_{Gi} + c_i$$

a_i , b_i , c_i are the cost coefficient and P_{gi} is the real power output of the i^{th} ancillary generator

OPF routine was run considering line flow limits at these conditions, which removes the congestion by minimizing the cost function of slack bus generator and ancillary generators together and rescheduling the output of the slack bus and the ancillary generators. Generations at bus-1 and ancillary generators are given in Table 3.5 From OPF routine marginal cost of removing congestion in the lines is recorded, which is shown in Table 3.6.

As described in previous chapter, by using active power tracing the proportion of usage of congested lines by generators at buses 1, 2 and 3 are given in Table 3.7. The costs allocated to these generators in the proportion of usage of line were computed and are given in Table 3.8.

Table 3 1· Desired Bilateral Transactions (IEEE-14 bus test system)

Bus number	Desired generation &load (MW)
Group-1	
Gen-2	159
Load-4	94
Load-8	8
Load-9	48
Load-10	9
Group-2	
Gen-3	100
Load-11	50
Load-13	50

Table 3.2: Transactions at Bus-1(Base Case) IEEE-14 bus system

Bus number	Generation and load (MW)
Gen-1	97.67
Loss	14.72
Load-2	21 7
Load-3	11 2
Load-7	29 5
Load-12	6.1
Load-14	14.9

Table 3 3· Effect of Desired Transaction Dispatch on Line Flow

(IEEE-14 bus test system)

Note Overloaded lines are with highlight rows

From bus	To bus	Line flow (MW)	Line flow (MVAR)	Line flow (MVA)	Line limit (MVA)	Max % of loading
2	1	-59 8	-8.9	60.4	300 0	20.2
1	8	37.2	12.8	39 4	200 0	19 7
2	4	87.1	2.4	87 1	200 0	43.6
2	8	27.5	10 2	29.4	200.0	14 9
2	9	82.4	5.3	82.6	90.0	91.8
8	3	32 6	22 4	39 6	1000 0	4 0
3	**11**	**52.4**	**7.2**	**52.9**	**50.0**	**105.7**
3	12	16.7	2 1	16 8	50 0	33.7
3	**13**	**52.4**	**11.5**	**53.6**	**50.0**	**107.2**
4	9	-10.4	10.8	14.9	200.0	8 7
6	5	0.0	-23.1	23.1	50 0	48.0
6	7	27.8	28 8	40 0	50 0	80.1
9	6	27.8	7 4	28.8	100.0	28.8
9	7	15.9	10.7	19.1	200.0	9 6
7	10	9.4	14.6	17 4	60.0	28.9
7	14	4.8	8 4	9 7	50 0	19.3
9	8	-23.2	-2.2	23 3	100 0	23.5
10	11	0.3	8.5	8.5	50 0	17.0
12	13	10.2	-0.2	10 2	50.0	20.5
13	14	10.5	-2.7	10.8	50.0	21.6

Table 3 4 Ancillary generator data (IEEE-14 bus system)

Gen bus no	Real power generation limit		Cost coefficients		
	Max (MW)	Min (MW)	a_i (Rs/MW^2–hr)	b_i (Rs/MW-hr)	c_i (Rs/hr)
11	100	0	1	3.72	35.2
13	100	0	1	3 72	35 2

Table 3.5 Generation at slack bus and auxiliary generators after OPF (IEEE-14 bus system)

Bus number	Generation (MW)
Gen-1	84.72
Auxiliary Gen-11	5.99
Auxiliary Gen-13	5.53

Table 3.6: Marginal cost of relieving congestion (IEEE-14 bus system)

From bus	To bus	MVA marginal cost (Rs/MW-hr)
3	11	19.0
3	13	21.4

Table 3.7· Contribution of generators to congested line flows (IEEE-14 bus system)

Gen bus no.	For line between buses	% Contribution to line flow
Gen-1	3&11, 3&12	10 37
Gen-2	3&11, 3&12	17 00
Gen-3	3&11, 3&12	72 62

Table 3.8. Allocation of congestion management cost to the generators (IEEE-14 bus system)

Generator bus no.	Cost allocated to generators	
	For line 3&11 (Rs/MW-hr)	For line 3&13 (Rs/MW-hr)
Gen-1	2.76	3 11
Gen-2	3.86	4.34
Gen-3	12.39	15 71

3.5.1.2 Voltage regulation cost allocation using reactive power tracing

The voltages of only those buses violating the limits after the OPF run in the previous section are given in Table 3.9. An SVC was considered to be connected at bus number 14 to bring up voltage above the assumed minimum limit 0.96 p u The value of MVAR supplied by shunt was computed from a load flow run which is 25.8 MVAR. The bus voltages after the placement of SVC are given in Table 3 9

Table 3.9: Effect on bus Voltages after placement of SVC (IEEE-14 bus system)

Bus no	Voltage (p u) (without SVC)	Voltage (p u) (with SVC)
11	0 94518	0 96723
13	0 95552	0 98206
14	0 94637	1 01514

By tracing reactive power as described in the previous chapter, the contribution of reactive source (IEEE-14 bus system has five reactive sources) to reactive load at buses 11, 13 and 14 are given in Table 3 10

Typical value of operating cost of shunt device (SVC) is 3500 Rs/MVAR-Year [2]. To provide 25 8 MVAR, as computed from the load flow, the cost of shunt device per hour is 10 31 Rs/hr This cost is divided among buses 11, 13 and 14 where originally voltage violation was seen in the ratio of their increment in the voltage magnitude This is given in Table 3 11. The cost associated with each bus is allocated to reactive power sources in proportion of their contribution to the reactive power load at these buses which is shown in Table 3.12

Table 3 10· Contribution of reactive sources to buses that violate voltage limit (IEEE-14 bus system)

Reactive sources bus no	% Contribution to reactive load		
	At bus	At bus	At bus
1	18 39	28 03	2 62
2	10.14	13 53	4 59
3	27 29	44 96	0
4	13.11	11 01	16.54
5	31 08	3 47	76 25

Table 3.11 Cost of shunt allocated to bus whose voltage is regulated (IEEE-14 bus system)

Bus no	Cost of shunt allocated to the bus (Rs/hr)
11	1 94
13	2 33
14	6 04

Table 3.12: Allocation of cost to reactive sources (IEEE-14 bus system)

Reactive sources bus no	Cost allocated to reactive sources			Total cost allocated to source buses (Rs/hr)
	At bus 11 (Rs/hr)	At bus 13 (Rs/hr)	At bus 14 (Rs/hr)	
1	0 357	0 653	0 159	1 169
2	0 197	0 315	0.277	0 789
3	0.529	1 024	0.000	1 553
4	0 254	0 256	1 00	1 510
5	0 600	0.079	4 61	5.289

3.5.2 IEEE-30 bus test system

Fig. 2.7 shows the modified IEEE-30 bus test system. The generator and load data including MVAR limits of the generators are shown in the Table B 1 Transformer and line data are provided in the Table B.2 and B 3, respectively

3.5.2.1 Congestion management cost allocation using active power tracing

In this system, five groups of bilateral contracts have been considered Group-1 makes power transfer from bus 2 to bus 4, group-2 makes transfers from bus 5 to bus 5, group-3 makes transfer from bus 8 to buses 7 and 8, group-4 makes transfer from bus 11 to bus 9 and group-5 makes transfer from bus 13 to buses 12 and 14. Table 3 13 presents desired generation and load data of these five groups Generator at bus-1 is made to supply load at other buses and losses in the system given in Table 3 14 With these transaction conditions a load flow was run The loss to be supplied by generator-1 given in Table 13.4, pertains to the base case load flow. The line rating and flow in the lines are shown in Table 3.15 From Table 3.15, it can be observed that the transmission lines between buses 12 & 14 and buses 27 & 29 get overloaded To remove congestion, ancillary generators are connected at buses 14 and 29. They had initially no generation The real power generation limits and cost characteristics of these ancillary generators are given in Table 3.16

OPF routine was run considering line flow limits at these conditions to remove the congestion by minimizing the cost function of slack bus generator and ancillary generators together and rescheduling the output of the slack bus generator and the ancillary generators. Generation at bus-1 and ancillary generators is given in table 3.17 From OPF routine marginal costs of removing congestion in the lines are recorded, which is shown in Table 3.18.

Table 3.13: Desired Bilateral Transactions (IEEE-30 bus test system)

Bus number	Desired generation &load (MW)
Group-1	
Gen-2	40
Load-4	40
Group-2	
Gen-5	31
Load-5	31
Group-3	
Gen-8	50
Load-7	20
Load-8	30
Group-4	
Gen-11	50
Load-9	50
Group-5	
Gen-13	50
Load-12	10
Load-14	40

Table 3.14: Transactions at Bus-1 (Base Case) for the IEEE-30 bus system

Bus number	Generation and load
Gen-1	119.45
Loss	10 15
Load-3	12 0
Load-10	5 8
Load-15	8 2
Load-16	3 5
Load-17	9 0
Load-18	3.2
Load-19	9.5
Load-20	2.2
Load-23	3 2
Load-24	8 7
Load-26	3 5
Load-29	12 0
Load-30	11.0

Table 3.15. Effect of Desired Transaction Dispatch on Line Flow

(IEEE-30 bus test system)

Note· Overloaded lines are with highlight rows

From Bus	To Bus	Line flow (MW)	Line flow (MVAR)	Line flow (MVA)	Line limit (MVA)	Max % of loading
1	2	67.8	1.3	67.8	100.0	67 8
1	3	51.7	18 4	54.9	150 0	36 6
2	4	41.4	17 1	44.8	50 0	89 6
2	5	22 8	14 8	27.2	50.0	54 4
2	6	42.8	17 2	46.1	50 0	92 2
3	4	38.5	15.0	41.3	45 0	91 8
4	6	8.3	1 4	8.4	50.0	16 9
4	12	30.3	28.2	41.4	50 0	82 8
5	7	22.5	5.3	23.1	50 0	46 2
6	7	-2.2	4 4	5 0	100.0	5.0
6	8	-11.8	-9 1	14.9	50 0	30 0
6	9	28.8	9.5	30.3	50 0	60.6
6	10	16 5	8 4	18.6	50 0	37 1
6	28	18.7	6.5	19.8	50.0	39 6
8	28	8.2	3 6	8 9	50.0	17 8
10	9	-28.8	-12 4	31 3	50.0	63 6
9	11	-50.0	-15 9	52.5	100.0	54.5
10	17	3.6	4 1	5 4	10.0	54.4
10	20	10 6	17 0	20.0	50.0	40.1
10	21	16.9	10.5	19.9	50.0	39.9
10	22	8.4	4 9	9 7	50.0	19.4
12	13	-50.0	-20 0	53.8	60.0	92.4
12	**14**	**30.4**	**12.3**	**32.8**	**20.0**	**164.1**
12	15	30.8	28.4	41.9	50.0	79.9
12	16	9.1	3 8	9.8	50.0	19.6
14	15	-10 9	8 0	13.5	50.0	27.2
15	18	5.0	12.4	13.4	50.0	26.7
15	23	5.1	-1.7	5.4	50.0	10.7
16	17	5.5	1.8	5.7	50.0	11.5
18	19	1 6	-9.1	9.2	50.0	18.6
19	20	-7.9	-15.2	17 1	50 0	34.8
21	22	-0.7	-1 0	1 2	50.0	2 4
22	24	7.6	3.8	8 5	50.0	17.0
23	24	1 8	-3 4	3.9	50.0	7 8
24	25	0.6	-2 5	2.6	50.0	5.2
25	26	3.5	2.4	4.3	50.0	8.5

Table 3 15 cont.

25	27	-2 9	-4.9	5 7	50 0	11 6
28	27	26 8	12.6	29.6	30 0	98 7
27	**29**	**13.6**	**2.3**	**13.8**	**13.0**	**105.9**
27	30	10 2	2 0	10 4	50 0	20 8
29	30	1.1	0.6	1.3	50 0	2 5

Table 3.16: Ancillary generator data (IEEE-30 bus system)

Gen bus no.	Real power generation limit		Cost coefficients		
	Max (MW)	Min (MW)	a_1 (Rs/MW^2–hr)	b_1 (Rs/MW-hr)	c_1 (Rs/hr)
14	100	0	1	3.72	35.2
29	100	0	1	3.72	35 2

Table 3 17 Generation at slack bus and ancillary generators after OPF (IEEE 30-bus system)

Bus number	Generation (MW)
Gen-1	94.0
Auxiliary Gen-14	22.0
Auxiliary Gen-29	1.0

Table 3.18 Marginal cost of relieving congestion (IEEE-30 bus system)

From bus	To bus	MVA marginal cost (Rs/MW-hr)
12	14	339.2
27	29	239.9

As described in the previous chapter, the proportion of usage of congested lines by generators at buses 1, 2, 5, 8, 11 and 13 are given in Table 3 19. The costs allocated to these generators in the proportion of usage of line was computed and are given in Table 3.20.

Table 3.19: Contribution of generators to congested line flows (IEEE-30 bus system)

Gen. bus no	% Contribution to line flow	
	Line between buses 12-14	Line between buses 27-29
Gen-1	27.42	51 58
Gen-2	10.32	19.41
Gen-5	0.0	1.73
Gen-8	0.0	27.29
Gen-11	0.0	0 0
Gen-13	62.27	0 0

Table 3.20: Allocation of congestion management cost to the generators (IEEE-30 bus system)

Generator bus no.	Cost allocated to generators	
	For line between 12&14 (Rs/MW-hr)	For line between 27&29 (Rs/MW-hr)
Gen-1	93.01	123.74
Gen-2	35.01	46.56
Gen-5	0 0	4.15
Gen-8	0.0	65.47
Gen-11	0.0	0.0
Gen-13	211.22	0.0

3.5.1.2 Voltage regulation cost allocation using reactive power tracing

The voltages of only those buses violating the limits after the OPF run in the previous section are given in Table 3 21 An SVC was considered to be connected at bus number 19 to bring up voltage above the assumed minimum limit 0.95 p u. The value of MVAR supplied by SVC was computed from a load flow run which is 14.6 MVAR The bus voltages after the placement of SVC are given in Table 3.21.

Table 3.21. Effect on bus voltages after placement of SVC (IEEE-30 bus system)

Bus no	Voltage (p u) Without SVC	Voltage (p.u) With SVC
18	0 93053	0 97122
19	0 94011	0 98797
30	0 94616	0 95992

By tracing reactive power as described in the previous chapter, the contribution of reactive source (IEEE-30 bus system has six reactive sources) to reactive load at buses 18, 19 and 30 are given in Table 3 22

Typical value of operating cost of shunt device (SVC) is 3500 Rs/MVAR-Year [2] To provide 14.6 MVAR, as computed from the load flow, the cost of shunt device per hour is 5.83 Rs/hr. This cost is divided among buses 18, 19 and 30 where originally voltage violation was seen in the ratio of their increment in the voltage magnitude This is given in Table 3 23. The cost associated with each bus is allocated to reactive power sources in proportion of their contribution to the reactive power load at these buses which is shown in Table 3.24

Table 3 22 Contribution of reactive sources to buses that violate voltage limit (IEEE-30 bus system)

Reactive sources bus no	% Contribution to reactive power load		
	At bus 18	At bus 19	At bus 30
1	0 61	0.61	7 87
2	3.82	3 82	49.47
5	0.00	0.00	0 00
8	3 17	3 17	41.15
11	23.87	23 87	0 00
13	68 53	68 53	1 52

Table 3.23: Cost of shunt allocated to bus whose voltage is regulated (IEEE-30 bus system)

Bus no	Cost of shunt allocated to bus (Rs/hr)
18	2.32
19	2 73
30	0.784

Table 3.24. Allocation of cost to reactive sources (IEEE-30 bus system)

Reactive sources bus no	Cost allocated to reactive sources			Total cost allocated to source buses
	At bus 18 (Rs/hr)	At bus 19 (Rs/hr)	At bus 30 (Rs/hr)	
1	0.020	0 020	0 062	0.102
2	0.090	0 104	0.390	0 584
5	0.000	0.000	0.000	0 000
8	0.074	0.087	0.323	0.248
11	0 554	0.652	0.000	1 206
13	1.590	1 870	0.012	3.472

3.6 Conclusions

This chapter has presented methods of allocating congestion costs to the transactions that are responsible for the congestion in an "equitable" manner and regulation of bus voltage through shunt compensating devices and allocating their cost amongst the sources. The proposed methods use OPF in deregulated market conditions Presence of bilateral (and multilateral) transactions has been considered. The studies have been conducted on IEEE-14 bus and IEEE-30 bus test systems. From the results presented in this chapter, following main conclusions can be made.

1 Congestion in the lines can be removed without curtailment of desired transaction through additional supports from ancillary generators.
2 OPF provides the generations required from the ancillary generators and loss makeup (slack) generators to manage the congestion
3 Cost of congestion can be allocated equitably to the market participants based on their usage of the congested lines obtained from the active power tracing
4 Higher the contribution to the flow in the congested line by a generator, higher will be the penalty
5 Bus voltages can be improved by using shunt devices and their cost can be allocated to the market participants by using reactive power tracing
6 Higher the increment of voltage at a bus, higher will be the cost allocated to these buses and in turn higher will be the penalty on sources supplying load at these buses.

Chapter 4

Conclusions

In a deregulated power industry, where there are many buyers and sellers, the access to the transmission system by generators and customers should be managed in a non-discriminatory manner In a deregulated market, it is possible that the trades between market participants can result in overloading of some of the electrical network components such as lines, transformer etc and bus voltages violating their limiting values The trading arrangements can be arrived at analytically with the help of a constrained optimal power flow solution. There can be an approach in which ISO may curtail the desired initial power transactions in a manner to bring the system within security limit. The present work made an attempt to present an OPF formulation to manage congestion without any curtailment of transactions and also regulating voltages within limit through use of ancillary sources. The cost of these ancillary services are required to be distributed equitably to all market participants The main contributions of this thesis have been

1. The usage of active and reactive power tracing to allocate the cost of congestion and cost of voltage regulation in equitable manner, the use of ancillary and loss make up generators and finding their settings through OPF for congestion management without curtailment of desired transactions.
2. Proposing a simple strategy for allocation of congestion management cost amongst various market participants, suitable for bilateral as well as multilateral transactions, using active power tracing
3 Managing voltage profile and allocating cost of voltage regulation amongst various market participants using reactive power tracing.

The studies were carried out on the modified IEEE-14 and IEEE-30 bus test systems The main findings of the thesis are given below.

In Chapter-2, the active and reactive power tracing were presented which can be used to resolve some of the difficult issues of the deregulated market such as pricing and congestion cost management. In competitive environment, this method seems to be useful in ensuring fairness and transparency in the operation of the electricity supply system. For active power tracing, both real power flow and complex current flow in lines were considered separately. For reactive power tracing, complex current flow in lines have been considered The test results obtained in this chapter provide the following main conclusions:

1 The contribution of generators to line flows in case of active power tracing is same as obtained by considering either the real power or the complex current flow in lines.
2 The domain and common might be different for the real and reactive sources for the same system
3. The result demonstrates that this approach can assess the contributions made by each generator in the system.

In Chapter 3, an OPF routine has been used to manage the congestion, using ancillary generators at suitable locations in the system without curtailment of the desired transactions A simple strategy for allocation of cost of congestion and voltage regulation amongst the various market participants has been suggested. From the results presented in this chapter, the following main conclusions are drawn

1 Congestion in the lines can be relieved without curtailment of desired transactions through additional supports from ancillary generators. The OPF provides the generation required from the ancillary and make-up (slack) generators to manage the congestion

2. Cost of congestion can be allocated equitably to the market participants based on their usage of the congested lines obtained from the active power tracing
3. Higher the contribution to the flow in the congested line by a generator, higher will be penalty imposed upon it
4. Bus voltages can be improved by using shunt devices and their cost can be allocated to the market participants with the help of reactive power tracing
5. Higher the increment of voltage at a bus, higher will be the cost allocated to these buses and in turn higher will be the penalty on the sources, supplying reactive power loads at their buses.
6. Cost allocation strategy suggested in this chapter is quite simple. It can be adopted to both bilateral and multilateral contracts.

The following future scopes of research are also identified

1. The present study has considered constant real and reactive power loads However, more accurate customer response can be modeled using generalized and practical load models.
2. In Chapter 3, the losses were considered to be made up from one of the generator buses. A detailed model considering the procurement of losses from any bus by any trade may be formulated
3. Voltage regulation cost based on marginal pricing can be used to remunerate the suppliers and to charge the consumers of these services

Bibliography

1 Perveen Kumar, Optimal Power Dispatch in Deregulated Market Considering Congestion Management, MTech Thesis, Indian Institute of Technology, Kanpur, February 2000

2 Ravindra Kumar Verma, Real and Reactive Power Pricing in a Deregulated Electricity Market Including FACTS Devices, MTech. Thesis, Indian Institute of Technology, Kanpur, May 2000

3 Lorrin Philipson and H Lee Willis, Understanding Electric Utilities and Deregulation, Marcell Dekker Inc., New York, 1999

4 Marija Ilic, F. Galiana and L Flink, Power System Restructuring. Engineering and Economics, Kluwer Academic Publishers, Boston, MA, 1998.

5 Power World Simulator User's guide Version 6.0, Power World corporation

6 Web site for Test Data of Power System Problems
http //www ee.washington edu

7 Mesut E Baran, Venkat Banunarayanan and Kenneth E Garren, "Equitable Allocation of Congestion Relief Cost to Transactions", IEEE Transactions on Power Systems, vol 15, no 2, May 2000, pp 579-585.

8 Julian Barquin Gil, Tomas Gomez San Roman, Jusan Jose Alba Rios and Pedro Sanchez Martin, "Reactive Power Pricing A Conceptual Framework for Remuneration and Charging Procedures", IEEE Transactions on Power Systems, vol 15, no 2, May 2000, pp 483-489

9. R. S. Fang and A K David, "Optimal Dispatch Under Transmission Contracts", IEEE Transactions on Power Systems, vol 14, no. 2, May 1999, pp. 732-737.

10. M. Huneault, F. D. Galiana and Lester Fink, "Power System Restructuring Engineering and Economics", Proceedings of 13th PSCC in Trondheim, June 28-July 2, 1999, pp 19-31.

11. Marino Ventosa, Andres Ramos and Michel Rivier, "Modeling Profit Maximization in Deregulated Power Markets by Equilibrium Constraints", Proceedings of 13th PSCC in Trondheim, June 28-July 2, 1999, pp. 231-237

12 A. Berizzi, G Demartini, M Delfanti, P Marannio and G Rizzi, "Security Constrained OPF for Optimal Transaction Scheduling in an Open Access Environment", Proceedings of 13th PSCC in Trondheim, June 28-July 2, 1999, pp 1214-1219.

13 Javier Garcia, Jaime Roman, Julian Barquin and Avelino Gonzalez, "Strategic Bidding in Deregulated Power System", Proceedings of 13th PSCC in Trondheim, June 28-July 2, 1999, pp. 258-264.

14. R. S. Fang and A K. David, "Transmission Congestion Management in an Electricity Market", IEEE Transactions on Power Systems, vol 14, no. 3, August 1999, pp. 877-883.

15. Daniel Kirschen and Goran Strbac, "Tracing Active and Reactive Power between Generators and Loads Using Real And Imaginary Currents", IEEE Transactions on Power Systems, vol 14, no. 4, November 1999, pp 1312-1319.

16 A K. David, "Dispatch Methodologies for Open Access Transmission Systems", IEEE Transactions on Power Systems, vol 13, no 1, February 1998, pp 46-53.

17. Francisco D. Galiana and Marija Ilic, "A Mathematical Framework for the Analysis and Management of Power Transaction Under Open Access", IEEE Transactions on Power Systems, vol 13, no 2, May 1998, pp. 681-687

18 Harry Singh, Shangyou Hao and Alex Papalexopoulos, "Transmission Congestion Management in Competitive Electricity Market", IEEE Transactions on Power Systems, vol 13, no. 2, May 1998, pp 672-680

19 J. Bialek, "Allocation of transmission Supplementary Charge to Real and Reactive Loads", IEEE Transactions on Power Systems, vol 13, no. 3, August 1998, pp. 749-754.

20. A. Bart, M. Benahmed, R Cherkaoui, G. Pitteloud and A. Germond, "Long Term Energy Management Optimisation According to Different Type of Transactions", IEEE Transactions on Power Systems, vol. 13, no 3, August 1998, pp. 804-809.

21. Shangyou Hao, George A. Angelidis, Harry Singh and Alex D Papalexopoulos, "Consumer Payment Minimization in Power Pool Auctions", IEEE Transactions on Power Systems, vol. 13, no. 3, August 1998, pp 986-991

22. John W M. Cheng, Francisco D Galiana and Donald T. McGillis, 'Studies of Bilateral Contracts with Respect to Steady State Security in a Deregulated Environment", IEEE Transactions on Power Systems, vol.13, no 3, August 1998, pp 1020-1025.

23. Joon Young Choi, Seong-Hwang Rim and Jong-Keun Park, "Optimal Real Time Pricing of Real and Reactive Powers", IEEE Transactions on Power Systems, vol.13, no. 4, November 1998, pp. 1226-1231.

24. A.J. Conejo and J. A. Aguado, "Multi-Area Coordinated Decentralized DC Optimal Power Flow", IEEE Transactions on Power Systems, vol 13, no. 4, November 1998, pp. 1272-1278.

25. Young-Moon Park, Jong-Bae Park, Jung-Uk Lin and Jong-Ryul Won, "An Analytical Approach for Transaction Costs Allocation in Transmission System", IEEE Transactions on Power Systems, vol 13, no 4, November 1998, pp 1407-1412.

26. Daniel Kirschen, Ron Allan and Goran Strbac, "Contributions of Individual Generators to Loads and Flows", IEEE Transactions on Power Systems, vol.12, no. 1, February 1997, pp 52-60

27 A K. David and R. S Fang, "Congestion Management of Electric Power System Under Open Transmission Access", Proceedings of the IEE conference on APSCOM, 1997, HongKong, pp 469-474

28 Wladyslaw Mielczarski, "Introducing Open Electricity Markets", Proceedings of the IEE conference on APSCOM 1997, HongKong, pp. 451-456.

29. Assef Zobian and Marija D. Ilic, "Unbundling of Transmission and Ancillary Services Part I· Technical Issues", IEEE Transactions on Power Systems, vol.12, no 2, May 1997, pp 539-548

30. Hugh Rudnick, Ruy Varela and William Hogan, "Evaluation of Alternatives for Power System Coordination and Pooling in a Competitive Environment", IEEE Transactions on Power Systems, vol. 12, no 2, May 1997, pp. 605-613

31. C. W. Yu and A. K David, "Security Related Long-Run Marginal Cost Analysis of Transmission Services", Proceedings of the IEE conference on APSCOM, 1997, HongKong, pp. 463-468

32 Janusz Bialek, "Topological Generation and Load Distribution Factors for Supplement Charge Allocation in Transmission Open Access", IEEE Transactions on Power Systems, vol.12, no 3, August 1997, pp 1185-1191

33 J Bialek, "Tracing the Flow of Electricity", IEE Proceedings on Generation, Transmission and Distribution, Part-C, vol. 143, July 1996, pp 313-320,

34 H H. Happ, "Cost of Wheeling Methodologies", IEEE Transactions on Power Systems, vol. 9, no. 1, February 1995, pp 147-156

35 J. W. Marangon, M. V. F. Pereira and J L R. Pereira, "An Integrated Framework for Cost Allocation in a Multi-owned Transmission System", IEEE Transactions on Power Systems, vol. 10, no. 2, May 1995, pp. 971-977

36. H. Rudnick, R. Palma, J.E Fernandez, "Marginal Pricing and Supplement Cost Allocation in Transmission Open Access", IEEE Transactions on Power Systems, Vol. 10, no 2, May 1995, pp 1125-1142

37 N G. Hingorani, Flexible "AC Transmission System", IEEE Spectrum, April 1993, pp. 40-45

Appendix A

Data For IEEE-14 Bus Test System

(At 100 MVA Base)

The IEEE-14 bus system data is taken from ref [6] The relevant data are provided in following tables.

Table A 1: Generator & Load data

a) Generator data

Gen Bus number	Voltage Magnitude (p u)	Reactive power limit (MVAR)		Reactive power demand (MVAR)
		Max	Min	
1(slack)	1.060	100	-45	0.0
2	1.040	50 0	-40 0	12 7
3	1.000	24 0	-6.0	0 0
4	1 010	40.0	0 0	19 0
5	1.090	24	-6	0 0

b) Load data

Load bus number	Reactive power demand (MVAR)	External Shunt Susceptance (p.u)
4	19.0	0.0
7	16.6	-0.19
8	1 6	0 0
9	-3.9	0.0
10	5.8	0 0
11	10.0	0.0
12	1.6	0 0
13	10 0	0.0
14	5.0	0.0

Table A.2. Transformer Data

Line No	From Bus	To Bus	Series Impedence		Tap Setting (p.u)
			Resistance (p.u)	Reactance (p u)	
1	8	3	0 0	0.2520	0 962
2	9	7	0 0	0 5561	0.969
3	9	6	0.0	0 2091	0.978

Table A.3 Line Data

Line No	From No	To Bus	Series Impedance		Shunt Susceptance full line charging (p.u)
			Resistance (p.u)	Reactance (p.u)	
4	1	2	0 01938	0 05917	0 528
5	1	8	0 05403	0 22304	0 0492
6	2	4	0 04699	0 19797	0.0438
7	2	9	0.05811	0.17632	0.0374
8	2	8	0.05695	0 17388	0.0340
9	4	9	0.06701	0 17103	0.0346
10	9	8	0 01335	0 04211	0.0
11	3	11	0 09498	0.19890	0 0
12	3	12	0 12291	0.25581	0 0
13	3	13	0 06615	0 13027	0.0
14	6	5	0.0	0 17615	0.0
15	6	7	0.0	0 11001	0.0
16	7	10	0.03181	0 08450	0 0
17	7	14	0.12711	0 27038	0 0
18	10	11	0.08205	0 19207	0.0
19	12	13	0.22092	0 19988	0 0
20	13	14	0.17093	0 34802	0.0

Appendix B

Data For IEEE-30 Bus Test System

(At 100 MVA Base)

The IEEE-30 bus system data is taken from ref [7] The relevant data are provided in following tables.

Table B 1· Generator & Load data

a) Generator data

Bus No	Voltage Magnitude (p u)	Reactive power limit (MVAR)		Reactive power demand (MVAR)
		max	min	
1	1.060	00 00	00 00	0 0
2	1 050	40 00	-40.00	0.0
5	1 010	40 00	-40.00	19 0
8	1 040	40 00	-10 00	30.0
11	1.040	24 00	-6 00	0.0
13	1.071	24 00	-6.00	0.0

b) Load data

Bus no	Load	External Shunt
	Reactive(MVAR)	
3	1 2	0 0
4	1 6	0 0
6	0 0	0.0
7	10.9	0.0
9	10.0	0.0
10	2 0	0 19
14	1.6	0.0
15	23	0 0
16	1.8	0.0
17	5.8	0.0

Table B.1 (b) Cont

18	21.0	0.0
19	6 0	0.0
20	0 7	0.0
21	11 2	0.0
23	1 6	0 0
24	6 7	0.043
26	2 3	0.0
29	0 9	0.0
30	1.9	0.0

Table B.2 Transformer Data

Line No	From Bus	To Bus	Series Impedence		Tap Setting (p.u)
			Resistance (0.u)	Reactance (p.u)	
11	6	9	0 0	0.2080	0 978
12	6	10	0.0	0 5560	0 969
15	4	12	0.0	0.2560	0 932
25	28	27	0.0	0.3960	0 968

Table B.3: Line Data

Line. No.	From No	To Bus	Series Impedance		Shunt Susceptance (p.u)
			Resistance(p u)	Reactance (p.u)	
1	1	2	0 0192	0 0575	0.528
2	1	3	0 0452	0.1852	0.048
3	2	4	0 0570	0 1737	0.0368
4	3	4	0 0132	0.0379	0.0084
5	2	5	0.0472	0 1983	0.0418
6	2	6	0 581	0 1763	0.0374
7	4	6	0 0119	0.0414	0.0090
8	5	7	0.0460	0.1160	0.0204
9	6	7	0 0267	0 0820	0.0170
10	6	8	0 0120	0 0420	0.0090
13	9	11	0.0	0 2080	0.0
14	9	10	0 0	0 1100	0.0
16	12	13	0 0	0 1400	0.0
17	12	14	0 1231	0 2559	0.0
18	12	15	0 0662	0 1304	0.0
19	12	16	0.0945	0 1987	0.0
20	14	15	0 2210	0.1997	0.0
21	16	17	0 0524	0 1923	0.0
22	15	18	0 1073	0.2185	0.0
23	18	19	0 0639	0.1292	0.0
25	19	20	0.0340	0.0680	0.0
26	10	20	0.0936	0.2090	0.0
27	10	17	0.0324	0.0845	0.0
28	10	21	0.0348	0.0749	0.0
29	10	22	0.0727	0 1499	0.0
30	21	22	0.0116	0.0236	0.0
31	15	23	0.1000	0.2020	0.0
32	22	24	0.1150	0.1790	0.0
33	23	24	0.1320	0.2700	0.0
34	24	25	0.1885	0.3292	0.0
35	25	26	0 2544	0.3800	0.0
36	25	27	0.1093	0.2087	0.0
37	27	29	0.2198	0.4153	0.0
38	27	30	0.3202	0 6027	0.0
39	29	30	0 2399	0.4533	0.0
40	8	28	0.0636	0.2000	0.0428
41	6	28	0.0169	0.0599	0.0130